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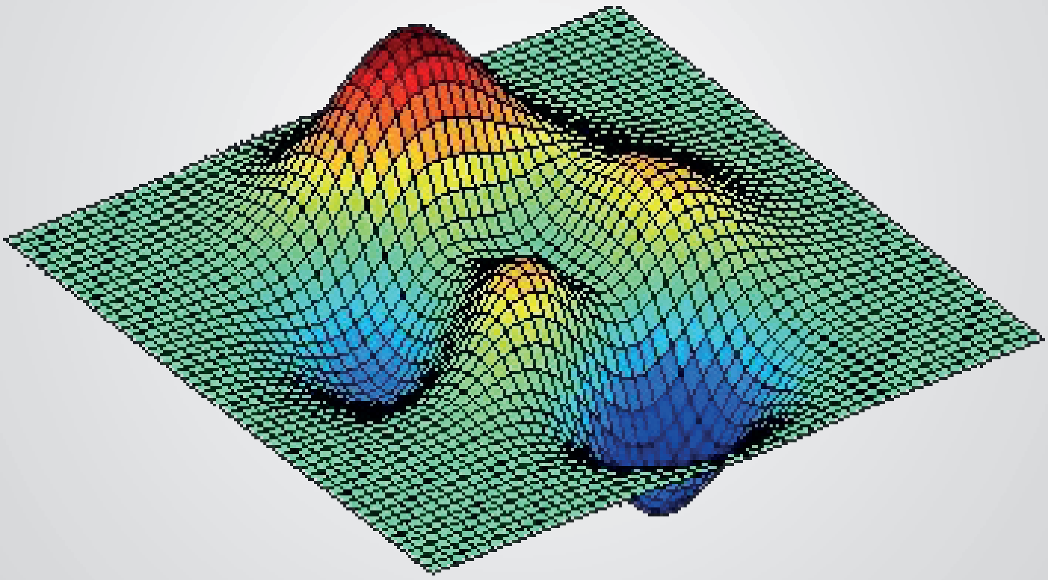

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CONTENT

RESEARCH OF DRYING OF BREWER PELLETS AIMED AT INCREASING OF ITS EFFICIENCY AND LOWERING OF POWER CONSUMPTION

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Abstract: *This paper presents the results of research of the drying process in the brewer pellets in aerovibrofluidized bed. The kinetics of drying of pellets in the suspension bed has been experimentally studied. We have received the generalized drying curve of brewer pellets at different process conditions. The generalized drying curve received as a collocation of the drying curves of brewer pellets at different process conditions is an indication of constant value of speed multiplied by time of drying, which simplifies the calculations of changes in moisture content during certain periods of the heat treatment of the product. We offered the relative ratio of energy consumption; proportionality factor of performance and bed depth; qualified expenditure power consumption indicator, which allow to reasonably choose conditions of brewer pellets drying and significantly improve the value of energy saving performance indicators of the drying process. There have also been introduced the parameters of qualified expenditure power consumption and the non-dimentional coefficient of power consumption.*

Keywords: drying, aerovibrofluidized bed, brewer pellets, energy efficiency

Introduce

One of the most energy-intensive processes in the food production process is the drying of raw materials and food products.

Breweries produce large quantities of various kinds of waste, the majority of which comprises osier pellets. This «byproduct» in its raw state is widely used by stock-breeders as a high-energy protein supplement for animal feeding stuff. In winter the problem of selling raw brewer pellets is virtually absent, but in summer farmers prefer to use green fodder. Meanwhile in the breweries accumulates a large amount of waste, the term of storage of which is limited to several tens of hours due to the rapid fermentation and mold formation.

Brewing waste is now often considered as a source of raw material with high nutritional value and biological activity used for feeding livestock and poultry. A medium power brewery annually produces 35,000 tons of brewer pellets which go to waste, and effective methods of preservation of the product (except for drying) do not exist. Drying of pellets is not used due to lack of energy-saving equipment [1, 2]. Such issues as large-tonnage waste recycling of brewer pellets should also be tackled because many factories pour them down the drain, causing the worsening of environmental situation in Ukraine.

Dry brewer pellets are widely used in meat, bread-baking and other food industries. Drying of brewery pellets to a final moisture content of 10% results in a long term of storage, which makes production and transportation over long distances cost-effective. The solid residue can be used for a whole range of valuable products, since it contains about 8 % of lipids, 26 % of proteins, 58 % of carbohydrates, as well as minerals, vitamins and other biologically active substances [3, 4].

Unfortunately, the existing drying processes of brewer pellets are extremely energy-consuming. Having modern technologies of thermal processing of high-materials (pellets contain more than 80 % of moisture) and at the same time imperfect technical equipment, it is necessary to develop advanced high-tech and low-power processes of brewer pellets and create equipment on the basis of new developments in the field of drying.

The most intensive process is the convective heat and mass transfer between the continuous gas medium and solid particles dispersed in a vibrofluidized pseudoliquified bed.

Vibrofluidized bed is formed either under the influence of vibrations only, or as a result of combined effect of vibrations and air movement. During the drying in the vibrofluidized bed particulate material may be brought into pseudoliquified condition due to the influence of vibrations on it. Vibratory oscillations of the working surface (grid) with a frequency of 40…60 Hz and an amplitude of 2…10 mm are generated by mechanical, hydraulic, electromagnetic vibrators. Shaking drier is successfully used for dewatering particulates prone to adhesion, which reduces energy costs compared to the cost of the material in the recycling or loading of wet material on a layer of a dry one. In this case, the speed of air is lower, the losses due to moisture pickup also decrease [5, 6].

The analysis of existing information on the subject suggests that the degree of influence of heat on heat labile components is primarily a function of temperature and duration of the thermal interference, as well as pH, amount of enzymes and other factors. Thus, the criterion for the heat resistance of products may be the maximum allowable temperature of heating in the drying process [7, 8].

Food drying in the pseudoliquified (aerovibrofluidized) bed is a common process, but it is understudied and has not been used for preserving brewer pellets [9].

The aim of the paper is research and development of the process of brewer pellets drying in a vibrofluidized bed, characterized by high energy efficiency.

Methodology of research and materials

The drying of pellets in the experimental assembly was carried out at the following values of parameters: temperature of the drying agent (air) – 50…70^{0}C; lattice vibrations: frequency F = 2…50 Hz, the amplitude A = 2…10 mm; air velocity – 0,5…3,0 m/s.

Such an upper limit of the drying temperature was chosen because at higher temperatures the proteins turn into unpalatable form, the pellets darken due to caramelization and formation of melanoids, part of the vitamins gets destroyed. At a temperature of less than 50°C, the drying process slows down, energy consumption increases.

To achieve the objectives we have developed the design of the experimental setup for drying of brewer pellets (Fig. 1 – the general view of the stand and Fig. 2 – the diagram of an experimental assembly), which is equipped with thermal, mechanical, control, measurement devices and registering apparatus [10, 11].

To investigate the brewer pellets drying parameters we have configured the measuring system (Fig. 3), which works in conjunction with a computer. A multi-channel system is intended for solving the tasks connected with the collection, processing, storage, visual display of information gathered both in real time and after summing up the measurements.

The measuring system consists of normalizers, commutators, analog-to-digital, digital-to-analog converters and software. There were used chromel-copel thermocouple sensors with point and differential measurements of process parameters.

Fig. 1. General view of the stand for experimental research of brewer pellets drier
1 – cyclone; 2 – exhaust fan; 3 – drying chamber; 4 – vibrator; 5 – sensors of drying parameters; 6 – regulators of power supply; 7 – the pressure fan; 8 – electric heater; 9 – sensor signal converter; 10 – measuring unit.

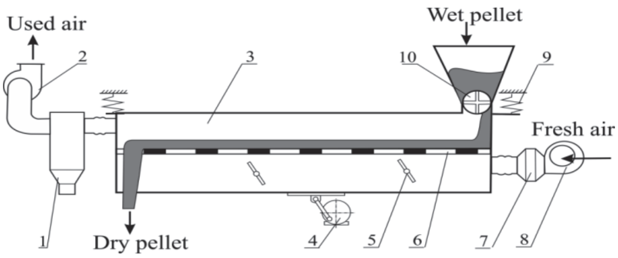

Fig. 2. The diagram of experimental drier of brewer pellets
1 – centrifugal collector; 2 – exhaust fan; 3 – drying chamber; 4 – vibrator; 5 – rotary plate; 6 – perforated screen; 7 – heater; 8 – the pressure fan; 9 – spring suspension; 10 – feeder unit.

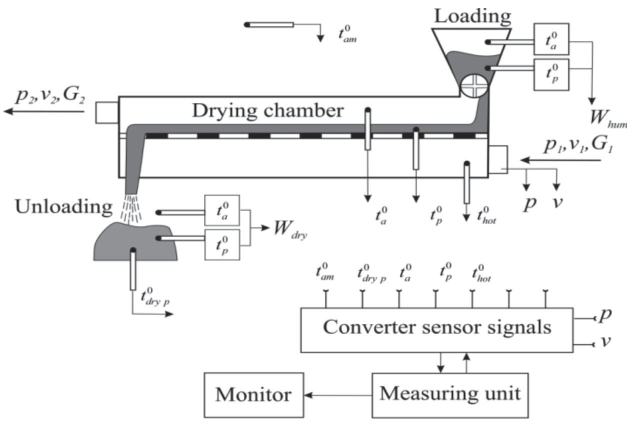

Fig. 3. Measuring diagram of the experimental dryer

t_{am} – ambient temperature; t_{hot} – hot air temperature; $t_{dry\,p}$ – the temperature of the dry product; t_a – ambient temperature above the product; t_p – the temperature in the layer of the product; W_{hum} – humidity of the raw pellets; W_{dry} – moisture of dry pellets; p – pressure of hot air; v – velocity of hot air.

The moisture of the pellets was determined in accordance with the instructions of technical-chemical control of the brewing industry in the «Sarmat» laboratory of the brewery. A portion of 8…10 g of raw pellet was placed in a weighing bottle and dried for 2 hours at a temperature of 60^0C and for 3 hours at a temperature of 105^0C. Calculation of moisture was carried out with the help of the formula

$$W = [(a - b)/(a - c)]\cdot 100, \quad (1)$$

where, a – is weight of the weighing bottle with the sample before drying, g; b – weight of weighing bottle with the sample after drying, g; c – weight of the empty weighing bottle, g.

Ambient humidity was measured with a hygrometer.

The temperature was measured with chromel-copel thermocouples located: t_{am} – in the environment; t_a – over the brewer pellets in the hopper and in the workroom; t_p – in the layer of the product; t_{hot} – under the layer of the product; $t_{dry\,p}$ – in a dry product with an output to analog recorder.

Measurement of the air flow rate and volumetric flow rate was done using hot-wire anemometer *Testo 415,* which allows to simultaneously measure air velocity and the temperature of it, which enabled us to confirm the readings of thermocouples. Measurements were made under the grid at the inlet to the operating chamber and at the outlet from the operating chamber. The magnitude of the hot air pressure was measured by changing the voltage supplied to the pressure fan.

The frequency of vibration was adjusted with a mechanical tachometer Testo 470. The density of the brewed pellets at various stages of the drying process was determined by weighing 0,001 m^3 of the substance. Regulation of the amplitude in the range of 1 to 10 mm was performed by moving the connecting rod pin in the direction from the center of rotation of the motor shaft. Supply air temperature control was carried out by changing the voltage supplied to the heater.

Before the start of the experiment the moisture of pellets was measured, and then the pellets had to undergo further drying. The tilt angle of the drying chamber which determines the speed of transportation of the drying product equals 8…10^0.

Brewer pellets, previously pressed resulting in a moisture content of 70…80%, were loaded into the receiving hopper of the experimental assembly. Due to the fact that the length of the experimental assembly (1000 mm) is not sufficient to completely dry the product, the batch of brewer pellets after each cycle was loaded again into the working chamber and the cycle repeated. Every 4 minutes samples were taken to determine the moisture content. The total drying time was about 1600 s.

III. Results and discussion

3.1. Investigation of the process of pseudoliquifying of the pellets.

Analysis of priori information on the application of complex effect on the dried product of coolant and vibration allowed to focus on the defining of such values as the flow rate of the coolant, the frequency and amplitude of the vibrations of the supporting sieve, the initial height of the filling layer, the influence of which on the hydrodynamics of the brewer pellets drying process is understudied.

Since the horizontal transfer of particles is predetermined by passing through layer of gas bubbles, the model of horizontal mixing should be presented as the diffusion of solid particles in a turbulent flow in a three-dimensional random velocity field and described as a random Markov process [12].

It has been found that the rate of upward flow of air should be sufficient to overcome the gravitational forces of filling of material particles, therefore, the most significant characteristic of the pseudoliquifying process is the value of air velocity.

Graphic relationship between hydraulic resistance Δp (pressure drop) of the product layer and the speed of the fluidizing air v_f in an unfilled section of the drying chamber was drawn according to experimental data. To receive these data, we used two U-shaped manometers, indicating pressure «under» and «above» the layer of brewer pellets. The rate corresponding to the inflection on the curves (Fig. 4) equal 2,0 m/s we shall call the velocity in beginning of pseudofluidization v_{f1} or the first critical pseudofluidization velocity. Starting with the velocity v_{f1} the value of Δp with increasing v_f almost does not rise. Upon reaching the second critical velocity of air v_{f2} begins the carry-over of a layer of the product even if it is underdried. Figure 4 shows a decrease in the value of Δp at $v_f > v_{f2}$, due to diminution of the material in the layer due to the carry-over of the individual particles.

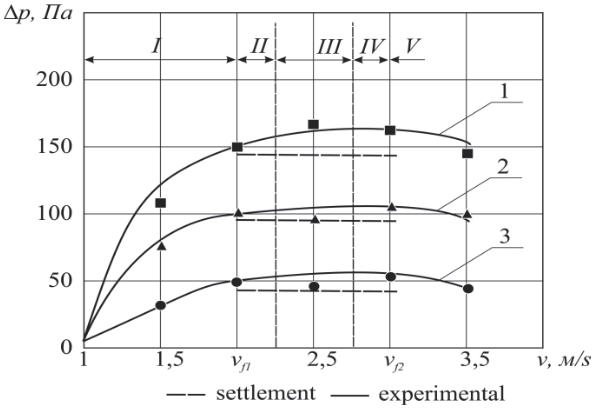

Fig. 4. Curves of pseudofluidization of brewer pellets at different heights of filling
1 – filling height is 20 mm; 2 – filling height is 30 mm; 3 – filling height is 40 mm

Analysis of the curves shows that the value of v_f is independent of the height of fluidizing layer of the product. The height of the layer determines only a resistance value Δp of the air flow passing through this layer. The calculated rate appeared to be a bit underestimated compared to experimental one due to averaging in calculating the load factor Δp.

In industrial dryer operation pseudofluidization velocity of the brewer pellets v_{op}, including scaling is 3…10 times greater than the starting velocity of fluidization v_{f1}. Therefore, in practical calculations, one can use the equation [6], which determines the ratio of the velocity of pseudofluidization

$$K_v = v_{op} / v_{f1}. \quad (2)$$

For experimental brewer pellets dryer the range of numbers of pseudofluidization K_v, in which there may be included a fluidized bed, the velocity is determined by the ratio of carry-over υ_{n2} and the start of pseudofluidization v_{f1}, i. e., $K = v_{f2} / v_{f1} = 3/2 = 1{,}5$. Liquefaction stage in Figure 4 are marked with the fields: *I* – the beginning of the disintegration of the layer; *II* – channel incrush of air; *III* – the destruction of channels and boiling, *IV* – active swirling boiling, *V* – carry-over. With an increase of fluidization occurs intensification of movement of the particles in the layer resulting in increase of its porosity, defined by the formula

$$\varepsilon = V_{air}/(V_{air} + V_{pel}), \quad (3)$$

where V_{air} – volume of air between the particles of the pellets; V_{pel} - the volume occupied by the pellets' particles.

The average value of porosity of unliquefied pellets is 0,6…0,7. During liquefaction – ε = 0,8…0,9, and under carry-over conditions ε equals one, since in this case the volume of air between the particles of pellet is much larger than volume occupied by the particles themselves.

The height of the pellets layer (filling) has been calculated experimentally, according to the well-known statement on the lower energy consumption at the lower layers, taking up more space than in the case of high layers on smaller areas. The loaded on the sieve layers of pellets from 10 mm to 60 mm were examined, and we found the following:

– at a height of layer of 10 mm drying rate is relatively high, but there is a danger of carry-over of underdried particles; at a layer height of 50…60 mm there is no constant drying rate and the process is significantly delayed in time; best results are obtained when loading the layer of 30 mm, when there were two periods of drying - the periods of constant and decreasing velocities.

3.2. Investigation of the kinetics of pellets drying in a suspension bed.

The main characteristics of the drying process of brewer pellets are kinetic functional connections between the product moisture changes and the duration of the process, the rate of change of humidity, pattern of temperature change of the material during the drying process under certain environmental conditions.

On the basis of the available information on the collocation and linearization of curves of drying [6], in order to reduce the number of experiments we conducted fractional factorial experiment that implements part (fractional replica) of the full factorial experiment of the 2^{4-1} type. The plan is assigned by generating relation $x_4=x_1x_2x_3$. Defining contrast is the relation $1 = x_1x_2x_3x_4$. Concurrently, the regression equation is of the form

$$y = b_0 + b_1x_1 +…+ b_px_p. \quad (4)$$

where y – the outputs vector – moisture of the brewer pellets; x_1, x_2, x_3, x_4 – vectors of the input parameters: x_1 – the temperature of the drying medium (air); x_2 – the sieve load (bed height of the product); x_3 - the speed of the drying agent; x_4 - parameters of the sieve vibration (frequency and amplitude).

The plan was executed by stepwise defining of the output value. At the same time were taken levels of varying input parameters, the reason for choosing which was mentioned above (Table 1).

Table 1

Parameters of the investigated process

Parameter	Symbol and unit	The lower level	The upper level
x_1	$t, {}^0C$	50	70
x_2	h_0, mm	20	40

x_3	v, m/s	2,5	3,5
x_4	F/A, Hz/mm	10/10	17/4

Step 1: $y^{(1)} = f(\tau)$ at x_1 = 50⁰C; 60⁰C; 70⁰C; x_2, x_3, x_4 = const.
Step 2: $y^{(2)} = f(\tau)$ at x_2 =20; 30; 40 mm; x_1, x_3, x_4 = const.
Step 3: $y^{(3)} = f(\tau)$ at x_3 =2,5; 3,0; 3,5 m/s; x_1, x_2, x_4 = const.
Step 4: $y^{(4)} = f(\tau)$ at x_4 =10/10; 13,5/7; 17/4 Hz/mm; x_1, x_2, x_3 = const.

On the basis of experimental pellet drying in order to receive constant weight under conditions of triplicate experiments and overlapping of their results within the measurement accuracy we plotted charts of drying and drying rate at the varying temperature of the drying agent, the sieve loads (of the initial bed height), speed of drying agent and the vibration parameters, the values of which are given in Table 1.

Stage 1. Experimental drying was carried out at three different temperature values of a drying agent (air) t: 50, 60 and 70⁰C. In each of three experiments bed height h_0 = 30 mm, the speed of the drying agent v = 2,5 m/s, the parameters of the sieve vibration (frequency F = 13,5 Hz and the vibration amplitude A = 7 mm) remained constant. As the drying agent we used air with temperature of 50, 60, 70⁰C and relative humidity of 30%. Initial moisture W^{raw} of the raw pellets was 400%, the final equilibrium water content – 9…10%.

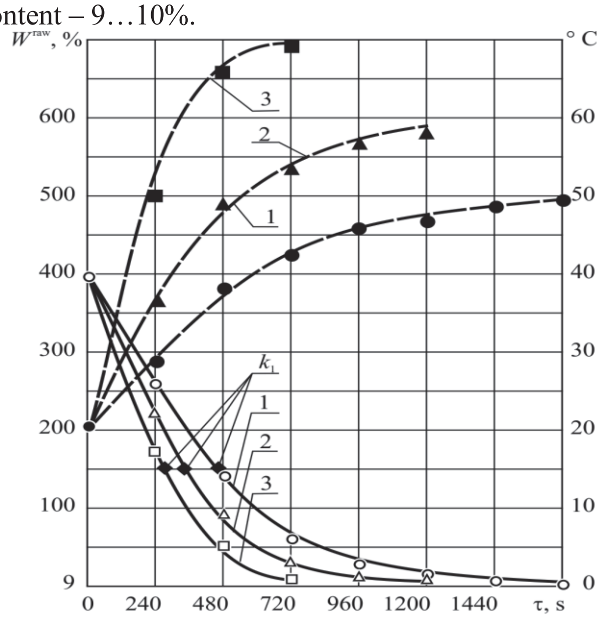

Fig. 5. Curves of changes in moisture content and temperature during the drying of brewer pellets at varying temperature of the drying agent

1 – at the temperature of the drying agent t = 50⁰C; 2 – at t = 60⁰C; 3 – at t =70⁰C.
The initial layer height of the product h = 30 mm; speed of the drying agent υ = 3,0 m/s; vibration parameters: F = 13,5 Hz, A = 7 mm.

Figure 5 shows graphical relations of the kinetics of humidity changes during the drying of brewer pellets $W^{raw} = f(\tau)$, obtained after processing the results of measurements of moisture loss given in the table.

Curves have a straight section from the beginning of drying to the point k_1. In this period, the drying process takes place at a constant speed and is identical to the process of evaporation of the liquid from the free surface, thus, on the basis of the Dalton's law it can be described by the expression:

$$-\frac{dW}{d\tau} = A(1-\phi_0)\exp\left(-\frac{A\rho_0 h_0}{\upsilon\rho_{dry\,a}100}\right), \quad (6)$$

where W is moisture content, %; τ – time, s; A - coefficient characterizing the mass transfer; φ – the initial relative humidity of the drying agent, %; ρ_0 and $\rho_{dry\,a.}$ – the density of freely poured layer of material and drying agent respectively, kg/m³; h_0 – initial height of the freely poured (dense) layer of material, m; v – speed of the drying agent, m/s.

The nature of the changes in moisture content suggests that the drying of the brewer pellets significantly depends on the temperature of the drying agent. When the air temperature equals 50⁰C (curve 1 in Fig. 5), the duration of the dewatering in the second period (at falling speed) is 2.5 times the duration of the dewatering in the first period (constant speed); with an air temperature of 60⁰C (curve 2 in Fig. 5) the ratio of the periods remains constant, but the overall drying duration at this temperature is reduced by 1.4 times; increasing the air temperature to 70⁰C (curve 3 in Fig. 5) results in a decrease in the total duration of the process in 2,3 times as compared with the first temperature control. More than half of the moisture contained in the product evaporates in the first period of drying, regardless of temperature. Analyzing all written above, it can be noted that in the first case the process is delayed in time and does not provide optimum performance of the process vessel and in case of temperature increase of the drying agent to 70⁰C there is a risk of failing to preserve the quality of the final product.

The analysis of temperature curves shows that the increase in temperature of the brewer pellets at the constant speed of drying passes rapidly. Later the temperature continues to increase, but its rate of growth slows down and stabilizes at approximately the equilibrium water content when drying process is considered complete. At this time, the temperature inside the product layer differs from the temperature of the hot air by several degrees (2…3^{0}C).

Step 2. Experimental drying was carried out at different initial bed height of the product: h_0 = 20 mm; h_0 = 30 mm; h_0 = 40 mm. In each of the experiments temperature of the drying agent t = 60^{0}C, rate of drying agent v = 3,0 m/s, the vibration parameters of the sieve F = 13,5 Hz and A = 7 mm remained constant. The parameters of the drying agent, the initial and the equilibrium moisture content of pellet are the same as in the first step.

Graphic processing of the experimental results is displayed in Figure 6 in the form of curves which show relation $W = f(\tau)$.

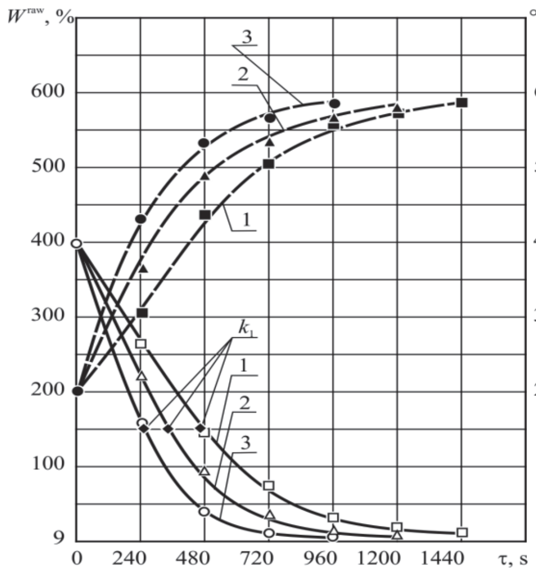

Fig. 6. Curves of changes in moisture content and temperature during the drying of brewer pellets at varying load (bed height)
1 – the initial bed height h_0 = 20 mm; 2 – at h_0 = 30 mm; 3 – at h_0 = 40 mm.
The temperature of the drying medium t = 60^{0}C; speed of the drying agent v = 3,0 m/s; vibration parameters: F = 13,5 Hz; A = 7 mm.

The curves in Figure 6 display an increase in the duration of the process by increasing the thickness of the product layer from 20 mm (curve 1) to 40 mm (curve 3). In the observed case, the total drying time increased by 1,5 times due to the slow evaporation of water in the second period. At the same time a high rate of dehydration in the first period of drying is maintained, which corresponds and is explained with the help of the components of the expression (4). The heating rate of the product varies, as indicated by the rapid rise in temperature in the first stage of drying (up to critical moisture content) and flattening of the curves in the second period. However, a noticeable effect of the thickness of the product layer on the drying time is less noticeable than the effect of the temperature of drying agent, as shown above (Fig. 5). By the end of the drying curves get closer and final drying is carried out in the same way at decreasing speed.

Stage 3. Experimental research on drying of brewer pellets was carried out at three different values of speed of the drying agent, constant parameters given in the picture captions (Fig. 7), the initial moisture content W^{mc} = 400%, the equilibrium moisture content W^{mc}_{eq} = 9...10%. As a drying agent we used ambient air with an initial temperature of 20 °C and relative humidity of 30%.

Comparison of curves 1 and 2 (Fig. 7) in the moment of reaching the equilibrium moisture content of the product shows that the increase in the speed of the drying agent from 2,5 to 3,5 m/s shortens the duration of the drying process by 67%. Thereby, the duration of the first drying period, when evaporates more than a half of the water contained in the brewer pellets, is affected by the change of speed of the drying agent less (20%) than by the change in temperature of a drying agent (Fig. 5) and the change in the height of the layer (Fig. 6). Temperature curves in this experiment are very close to each other, particularly in the second period, displaying the fact that the process takes place at relatively high and, consequently, energy-consuming, temperatures.

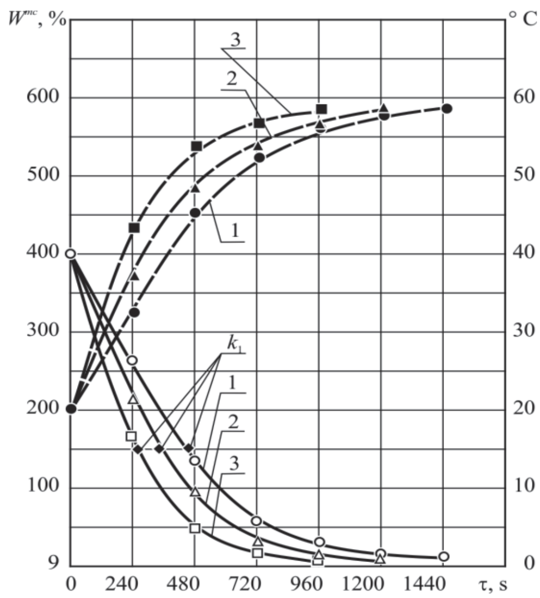

Fig. 7. Curves of change in moisture content and temperature during drying process of brewer pellets at varying speed of the drying agent

1 – at the speed of the drying agent v = 2,5 m/s; 2 – at v = 3,0 m/s; 3 – at v = 3,5 m/s.
The temperature of the drying medium t = 60^{0}C; the product's initial height h = 30 mm; vibration parameters: F = 13,5 Hz, A = 7 mm.

Step 4. We have investigated the batches of brewer pellets with free filling bed height h = 30 mm, the initial moisture content of 400%, which were blown by the hot air at t = 60^{0}C and velocity v = 3,0 m/s. A sieve with a product was cited in the vertical oscillation at a frequency of 10; 13,5; 17 Hz and an amplitude of 10, 7, 4 mm. The range and oscillation parameters were defined in a preliminary test of the drier with a product load and were taken by us as the most efficient from a wide range of parameters recommended by the authors [5, 13].

Drying curves 1, 2, 3 (Fig. 8) plotted within the range of change of vibration parameters display a slight (16%), reduction of the drying time in the transition from a relatively high frequency of 17 Hz to a lower frequency – 10 Hz. Frequencies of 10 and 13,5 Hz almost identically influence the duration of the process (curves 1 and 2), while the oscillation frequency equal or close to 17 Hz (curve 3) can be considered less effective.

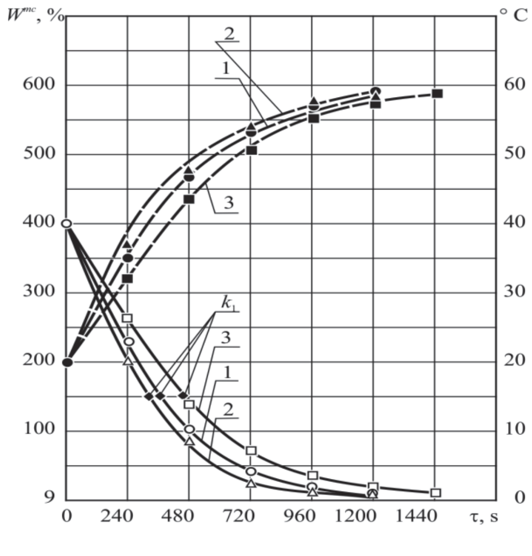

Fig. 8. Curves of change in moisture content and temperature during the drying of brewer pellets at varying parameters of sieve vibration
1 – at the oscillation frequency of the sieve F = 10 Hz and the amplitude A = 10 mm; 2 - at F = 13,5 Hz and A = 7 mm; 3 - at F = 17 Hz and A = 4 mm.
The temperature of the drying medium t = 60^{0}C; The product's initial height h = 30 mm; the speed of the drying agent υ = 3,0 m/s.

At the same time, the determining factor of occurrence of aerovibrofluidized bed, along with the speed of the air, is sieve vibration and the fact that all the previous results (steps 1, 2, 3) were obtained using motion parameters corresponding to the selected range. Therefore, curves 1 and 2 indicated the correct selection of the oscillation frequency F = 13,5 Hz and the amplitude A = 7 mm.

Comparing the results of the research, we made a conclusion about a significant impact on the drying temperature of the drying agent (Fig. 5) and the bed height of the product (Fig. 6). Less effective factors are the speed of the drying agent (Fig. 7) and the parameters of sieve vibration (Fig. 8). The latter is explained by the small range of permissible values of the factors mentioned.

The empirical formulae describing the change in moisture content of brewer pellets (Figure 5–8), were obtained with the help of the software «Curve Expert 1.3» and presented in the following form:

$Y = a + bx + cx^2 + dx^3$ – for the curves 1 and 2;

$y = a\cdot exp(-(b-x)^2/2c^2$ – for the curve 3

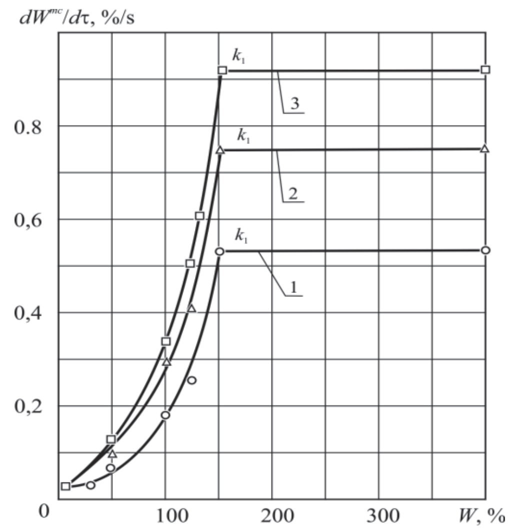

Fig. 9. Curves of drying speed of the brewer pellets obtained by graphical differentiation
1 – at the temperature of the drying agent t = 50^{0}C; 2 – at t = 60^{0}C; 3 – at t = 70^{0}C.
The initial product layer height h = 30 mm; speed of the drying agent υ = 3,0 m/s; vibration parameters: F = 13,5 Hz, A = 7 mm.

In order to further analyze the kinetics of drying grains we carried out graphical differentiation of curves of drying and plotted the charts of drying speed $dW^{mc}/d\tau = f(W)$ (Fig. 9).

Curves 1, 2, 3 (Fig. 9) during the process of drying the pellets in a pseudofluidized state have horizontal sections of the fixed speed corresponding to intensive drying, and slanting curves which indicate the falling speed. It is evident that higher temperatures of the drying agent correspond to the higher drying rate in the first period of the process. When reaching the critical point K_1, the speed begins to fall, and all the curves come closer and asymptotically approach the value of the equilibrium state. This drop can be explained by the reduction of the moisture content on the surface and an increasing of internal resistance of the heat transfer. Curves of speed of pellets drying of the second stage of research (varying of the bed height of the product) do not differ from the process intensity of the ones given above. A thinner layer of product dries more quickly.

To calculate the root-mean-square error of the measurements and determine whether the experimental distribution corresponds to the normal distribution law we used a graphical method of processing the results by comparing the experimental distribution curves with a set of theoretical curves. The root-mean-square deviation did not exceed 9,3%.

3.3. Determination of the process parameters on the basis of experimental data.

On the basis of the experimental brewer pellet drying to constant weight under condition of triplicate experiments and overlapping of their results within the measurement accuracy curves of drying and the rate of the product drying were obtained at varying temperatures of the drying agent (air), the sieve load (bed height), air speed and vibration parameters. When comparing the results of studies we have suggested that the most significant impact on the drying has air temperature (Fig. 5) and the bed height of the product (Fig. 6), while the influence of parameters reflected in the curves in Figures 7 and 8 are less important.

Combining the curves of drying of brewer pellets obtained in these modes, in a generalized curve (Fig. 10) by the method of V. Krasnikova [6] proves that he product of speed and drying time $N\tau$ is constant and simplifies calculations of changes in moisture content both in the first and second period of heat treatment of the product.

Analysis of the generalized curve characterizing the kinetics of drying of pellets displays that the experimental points lie practically on the same curve, plotted in coordinates $W^{mc} - W^{mc}_{eq} = f(N\tau)$.

The curves received allow to determine the drying time and the current moisture content of the product, but not to select an efficient mode, since there is no criterion for selection. Having included in the search of such a mode the values of performance and power consumption, we made a comparison of the experimental data on drying of pellets at different modes (Table 2).

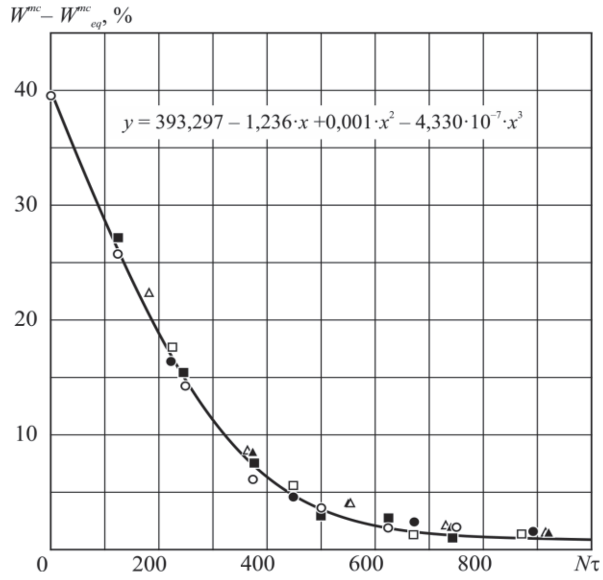

Fig. 10. The generalized curve of drying of the brewer pellets at various modes of drying

Mode 1. The temperature of the drying agent *t:* ○ – 50⁰C; Δ – 60⁰C; □ – 70⁰C.

The initial height of the layer of product filling h_0 = 30 mm; speed of the drying agent v = 3,0 m/s; vibration parameters: F = 13,5 Hz, A = 7 mm.

Mode 2. The initial height of the layer h_0: ● – 20 мм; ▲ – 30 мм; ■ – 40 мм.

The temperature of the drying agent t =60⁰C; speed of the drying agent v = 3,0 m/s; vibration parameters: F = 13,5 Hz, A = 7 mm.

Table 2

Comparison of experimental data on drying of brewer pellets at different modes

Pos.	Mode (fig. 3.11, 3.12)	Parameters of drying modes				Speed of drying, N	Duration of the 1st period, τ_1, h
		t, °C	h_0, mm	v, m/s	F/A, Hz/mm		
1	2	3	4	5	6	7	8
1	Mode 1.1	50	30	3,0	13,5/7	0,52	0,13
2	Mode 1.2	60	30	3,0	13,5/7	0,76	0,09
3	Mode 1.3	70	30	3,0	13,5/7	0,93	0,07
4	Mode 2.1	60	20	3,0	13,5/7	0,93	0,07
5	Mode 2.2	60	30	3,0	13,5/7	0,76	0,09
6	Mode 2.3	60	40	3,0	13,5/7	0,52	0,13

Continuation of the table 2

Duration of the 2nd period, τ_2, h	The total drying time, τ, h	Relation coefficient of energy consumption, K_{en}	Proportionality factor of performance and the layer height, K_p, 1/h	Qualified expenditure of electrical power ($\tau \cdot K_{en} \cdot K_p$), c.e.u.
9	10	11	12	13
0,33	0,46	1,00	30	13,8
0,24	0,33	1,23	30	12,2
0,13	0,20	1,50	30	9,0
0,20	0,27	1,23	20	6,6
0,24	0,33	1,23	30	12,2
0,27	0,40	1,23	40	19,7

Table 2 shows the nondimensional factor of energy K_{en}, which is defined as follows: the smallest defined capacity of electric equipment of the test bed according to one of the modes of drying is assigned with value equal to one. The coefficients of other modes were calculated on the basis of proportional relations of capacities.

Comparative analysis of the data in Table 2 is not the unambiguous definition of rational mode. In such way, if we choose energy consumption as the criterion for selecting the drying mode, the most economical would be considered the mode 2.1, at which conventional energy consumption is 6,6 c.e.u. (conventional electrical unit), and the drying rate – N = 0,93. However, the performance of the dryer is 1,5…2 times lower than in other modes under research. Low power consumption, high speed of drying, and the average value of the performance characterize the mode 1,3. Under industrial conditions, the temperature of the drying agent t can exceed 70^{0}C, when irreversible micro-processes on the surface of the product begin, leading to a rapid qualitative change in the structure of the product, which, in turn, prevents the intensity of water abstraction in the first period of drying. Modes 2.3 and 1.1 are the most energy consuming and prolonged in time ones, the drying process proceeds slowly at the speed N = 0,52, and hence, is characterized by low equipment performance.

On the basis of an examination of the modes it should be concluded that it is appropriate to conduct the process of drying of the pellets in the mode 1.2 at the air temperature t = 60^{0}C and conventional energy consumption of 12,2 c.e.u. At that the main criterion of the mode choosing is not the minimum power consumption, not a minimum drying time in general, but time, ensuring the preservation of high quality finished product [14].

IV. Conclusion

The experimental curves of changes in moisture content and temperature of the brewer pellets during the drying process at varying parameters of sieve vibration, layer height of the brewer pellets and speed of the drying agent, as well as the plotted generalized drying curve of the brewer pellets at various process modes and collocation of curves obtained at different modes in a single generalized curve indicated that the product of speed and drying time is constant, which simplifies calculations of changes in moisture content during certain periods of the heat treatment of the product.

We have offered the relative ratio of energy consumption; proportionality factor on performance and the layer height; conditional energy consumption indicator, which allow to reasonably choose rational modes of drying of brewer pellets.

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Experimental study on mechanical properties of NBR-based rubber mixture

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Abstract. *An experimental study has been conducted to determine some mechanical properties of NBR-based vulcanized rubber compound which is used for the production of O-shaped ring gaskets which are very common in the technological equipments used in the food-processing industry. The effects of the ageing process of the rubber on the parameters in question is also assessed. The parameters which are subject of the study are chosen to be such parameters which are needed in order to use the methods of 3D modeling and computer simulations in combination with the Finite element method and elasticity theory to perform analysis on the stress and deformational state of machine parts made of rubber. Conducting such analysis would allow the engineers to examine the influence of various factors related to the design of the machines on the distribution of stress within the rubber parts. This could be in favor of improving the design of the technological equipment and increase the life-span of the rubber parts.*

Key Words: NBR-based rubber compound, experimental study, mechanical properties, application in 3D FEM-based modeling

I. Introduction

Rubber is widely used material within the technological equipment used in the food processing industry. One of the most common application of the elastomers is related to the production of various gaskets intended to ensure proper insulation of environments filled with different fluids and/or operating at different pressure. It is crucial to prevent leakages and accidental mixing of fluids in the food processing equipment as one such leakage can cause a contamination of the food products and endanger the health of the consumers.

Efficient and reliable insulation is achieved by subjecting the rubber gaskets to a mechanical compressive loadings causing it to sustain deformation which is predominantly elastic. As the time passes however, ageing process of the rubber leads to irreversible change in the mechanical properties resulting in a residual plastic deformation and loss of functionality of the gasket which would require its replacement. Ageing can be accelerated either by aggressive chemical compounds are in direct contact with the gaskets or by subjecting the gasket to higher temperatures.

For the past two decades many elements related to the design of the technological equipment used in the food processing industry have been optimized and their functional characteristics have been improved. This optimization has been achieved by implementing advanced tools for enginery design such as CAD/CAM software products which by using the Finite element method (FEM) can determine and then visualize the distribution of the stress and deformation within 3D geometric models of various elements of the machines and apparatus used in the food processing industry.

Such advanced tools can be use to obtain information on the stress state within the gaskets and other rubber parts. This information can be used to assess the influence of different factors related to the design of the equipment and/or the rubber parts themselves. An optimization can be done aiming to prolong the life-span of the rubber parts and improve their reliability and functionality.

Knowledge of certain mechanical characteristics comes necessary in order to be able to use the means of 3D modeling combined with FEM and elasticity theory for obtaining of an accurate and useable picture of the distribution of the stress and deformation within the rubber parts inserted into the food-treating machines. Not only are some mechanical properties of rubber needed to be known, but how the ageing process of rubber affects them also comes essential.

The present article presents a study which has been conducted to determine some mechanical properties of NBR-based vulcanized rubber mixture which is most commonly used as material for O-shaped ring gaskets which are widely used in food-processing industry. The study also assesses the change of the determined mechanical properties due to the process of ageing of rubber.

The mechanical properties which are a matter of interest for the study are the modulus of elasticity E (also known as Young's modulus), tensile strength R_M and the rupture elongation A – properties needed for a numerical determination of the stress state of 3D geometric model by using FEM combined with