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THE BRIQUETTING PROCESS OF BREWERY WASTE IN A ROTARY GRANULATOR WITH A FLAT DIE IN THE TECHNOLOGICAL RECYCLING

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Keywords: *brewers' spent grain, kieselguhr, environmental pollution, compound feed, rotary granulator, rolling method, flat die, force distribution diagrams.*

Abstract. *Annually there is a lot of food waste in the form of kieselguhr and brewers' spent grain at breweries in Russia. In the pelleted form they are in use as components of compound feeds. Brewers' spent grain is a valuable brewing by-product with a limited shelf life (up to 3 days due to its organic composition) and high moisture content (80–85%). After the expiration of the shelf life, brewers' spent grain turns sour with the release of ammonia and carbon dioxide. The paper presents the results of studies on the granulation of brewers' spent grain and kieselguhr by pressing in a rotary granulator with a flat die and channels of variable cross-section. The research presents a developed physical and mathematical model of the rolling process. Equations have been obtained for determining the forces acting in the channel of variable cross-section of the flat die. For the pressed mixtures, diagrams of force distribution along the channel length in the flat die have been constructed. It allows us to forecast the change in pressure in the channel depending on the powder morphology. A schematic diagram of the technological line for the production of a nutritive feed additive using a modernized design of a rotary granulator with a flat die is presented. The developed technology allows raw brewers' spent grain to be converted into granules to reduce the environmental pollution.*

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Introduction

Annually, the large amounts of raw wet waste such as brewers' spent grain (BSG) and kieselguhr are generated at breweries in Russia. Existing methods for the disposal of brewers' spent grain require thorough preparation and special equipment. However, these methods do not guarantee environmental safety from biological contamination. The processing of BSG leads to significant costs both for transportation and for its conversion into a market product [1].

BSG is a by-product of brewing – the residue of barley (corn, rice, or oat) raw material after the production of wort. Most often, it is a suspension of seed particles and grain husks, rich in vegetable fiber. It is usually used as a feed additive to compound feeds in the diets of livestock and poultry [2, 3]. BSG contains a fairly large proportion of digestible protein (4% in fresh and 17% in dried form), which is almost 3 times higher than its content in barley. They also include the essential trace elements (phosphorus, calcium, magnesium, copper, iron), fatty acids, and vitamins E and F. Experimental results show that when fed to fattening bull calves, their weight gain increased by 14%. Consumption of recommended doses does not lead to any deviations in animal health [4]. BSG allows savings on consumed compound feeds. Indeed, the inclusion of spent grain in livestock diets reduces the cost of feed, while the weight gain of livestock increases by 9%. In liquid form, it does not store well and quickly turns sour within 48–72 hours. The shelf life of dry spent grain in powder form increases to 2 months, and of dry granulated spent grain – up to 18 months [5]. To convert BSG into powders or granules, drying using spray dryers or fluidized bed dryers is often used. These processes are energy-intensive, have high costs, and require large areas for equipment placement. A known technology also exists for the production of granulated compound feeds on roller presses or rotary granulators with ring or flat dies.

Worldwide, a huge amount of spent kieselguhr is generated. It contains organic substances that have settled on the particles during the beer filtration process. Kieselguhr can be used in industry as an adsorbent or an additive in the production of cement, ordinary and silicate bricks, as well as in agriculture as a fertilizer or additive to compound feeds. Kieselguhr is often used to improve soil structure [6]. This leads to its loosening and an increase in pore volume. As a result, the amount of retained moisture and nutrients increases. When plants are treated with kieselguhr, the uptake of metasilicic acid (H_2SiO_3), which is a source of available silicon that strengthens cell walls and enhances plant immunity, is facilitated. Kieselguhr is used in compound feeds for pigs as a natural mineral additive rich in silicon, calcium, and trace elements. This improves digestion and nutrient assimilation by increasing the number of bifidobacteria and lactobacilli. It enhances productivity and livestock survival. Spent kieselguhr, having absorbed proteins, sugars, other substances, and microorganisms from beer, like spent grain, cannot be stored for a long time [7]. Thus, for further use in compound feeds, kieselguhr must be dried, granulated, and disinfected.

Main body

We analyze the main properties and characteristics of BSG. Tables 1 and 2 present the chemical composition of fresh BSG and dried BSG, respectively [8].

Table 1. Chemical composition of fresh brewers' spent grain (per 1 kg)

Indicator	Liquid	Dry
Dry solids, g	232	887
Crude protein, g	58	217
Crude fiber, g	39	140
Nitrogen-free extractives (NFE), g	107	406
Crude fat, g	17	60
Vitamin E (tocopherol), mg	14	23
Vitamin B1 (thiamine), mg	0.2	0.6
Vitamin B2(riboflavin), mg	0.3	0.9
Vitamin B4 (choline), mg	510	1,300
Nicotinic acid (vitamin PP, niacin, vitamin B3), mg	13	36

As a result, BSG contains insoluble substances with vitamins; proteins precipitated as a result of boiling the mash, and products of the interaction of proteins with tannins. The liquid fraction of BSG contains lipid substances – triglycerides, free fatty acids, and phospholipids. Most of the vitamins contained in barley malt pass into the spent grain: vitamins E, B1, B2, B4, and nicotinic acid.

Table 2. Composition of dried brewers' spent grain (%)

Indicator	%	Indicator	%
Chemical composition, %		Microelements	
Moisture	8.67	Calcium	0.37
Crude protein	23.44	Phosphorus	0.5
Crude fat	7.75	Manganese, mg/kg	52
Crude ash	2.5	Zinc, mg/kg	105
Crude fiber	14.3	Ferrum, mg/kg	205
Nitrogen-free extractives (NFE)	43.44	Copper, mg/kg	15
Amino acids			
Lysine	0.86	Proline	2.05
Histidine	0.66	Glycine	0.79
Arginine	1.07	Alanine	0.94
Aspartic acid	1.35	Cystine	0.46
Threonine	0.77	Valine	1.06
Serine	0.89	Methionine	0.5
Glutamic acid	4.56	Leucine	0.57
Isoleucine	0.79	Phenylalanine	1.23
Tyrosine	0.61	Total amino acids	19.17
		Including essential amino acids	7.51

Kieselguhr particles are porous siliceous (diatomaceous) particles with sizes ranging from 0.001 to 0.01 mm. The organic component of spent kieselguhr is represented by brewer's yeast cells, proteins, and other organic substances filtered from beer.

Spent kieselguhr contains about 70–80% water and about 20–30% dry residue. Chemical composition of the dry residue of spent kieselguhr (wt. %): SiO_2 – (80.0–99.0); Al_2O_3 – (0.1–6.0); Fe_2O_3 <3,0; CaO – (0.5–2.0); Na_2O – (0.5–3.0); K_2O – (0.5–3.0); P_2O_5 – (0.1–0.2); TiO_2 – (0.5–3.0); MgO – (0.5–3.0); crude protein – 11.7; nitrogen – 1.5; glucosea – 0.43. The density of wet spent kieselguhr varies in accordance with its water content. For example, the density of spent kieselguhr with a moisture content of 71% is 1,160 kg/m^3 [7].

The most commonly used granulating equipment for such waste is a rotary granulator with a ring die, used in the production of compound feeds. However, such a granulator has a complex design, and the presence of generated fines during granulation complicates the control of its operation [9]. More promising is the use of a granulator with a flat die [10]. To develop the process of granulation of BSG and kieselguhr in a rotary granulator with a flat die and to determine the operating parameters, studies of the pressing process in a closed die with the production of compacts were conducted.

The paper presents the results of compression tests in a closed die with various binders and additives (Table 3). As binders, waste from the pulp and paper industry (lignosulfonate) and an aqueous sugar solution were used.

Table 3. Composition of mixtures for pressing in a closed die

Mixture component, wt %	**Number of mixture**				
	1	2	3	4	5
Dry spent grain	100	75	75	75	70
Kieselguhr	—	25	—	—	20
Sugar	—	—	25	12.5	10
25% LSS solution	—	—	—	12.5	—
Moisture	8	9	6	11	6

In the technological scheme for producing granulated feed additive, sugar can be replaced with beet molasses. It allows ones to utilize waste from beet sugar production and reduce the cost of the final product.

As a result of the compression tests, dependences of the changes in granule density and crushing strength on the specific pressing pressure and moisture content were obtained. According to Fig. 1, the density of the obtained compacts ranged from 800 to 1,200 kg/m^3. The dense and strong compacts begin to form at specific pressures in the range of 40 to 100 MPa. A further increase in the specific pressing pressure practically does not increase in granule density. The strength of the compacts varied from 0.1 to 1.5 MPa (Fig. 2).

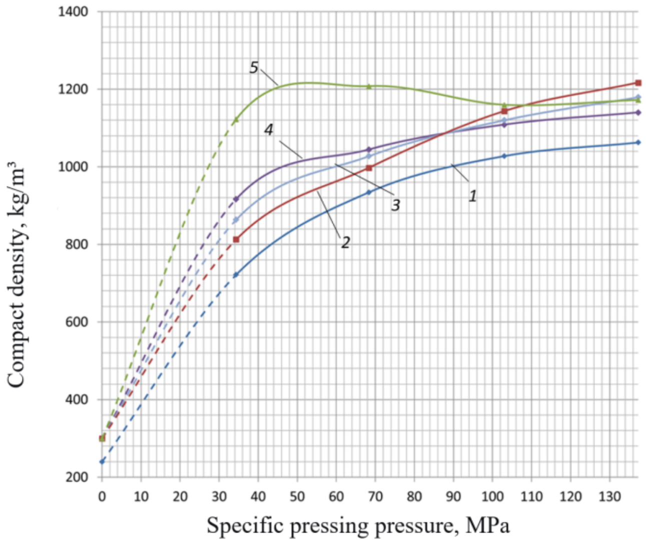


Fig. 1. Dependence of compact density on specific pressing pressure (curve numbers correspond to the mixture numbers given in Table 3)

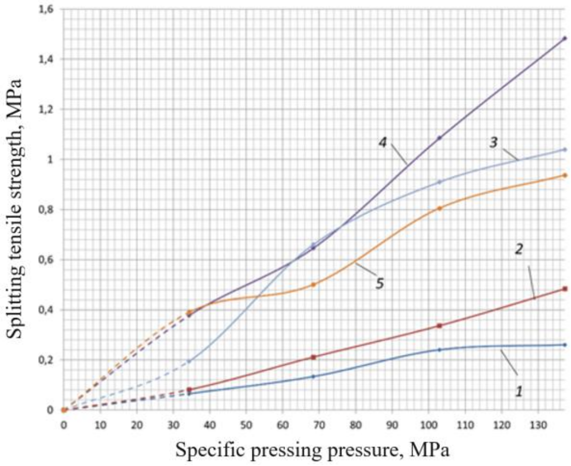


Fig. 2. Dependence of the splitting tensile strength of compacts on specific pressing pressure (curve numbers correspond to the mixture numbers given in Table 3)

The optimal value is a density of ρ_{pr} = 1,000 kg/m^3. It corresponds to a change in the splitting tensile strength in the range of 0.2–0.8 MPa, achieved at a specific pressure of 80 MPa. The obtained granulated product exhibits biological stability, does not rot during storage, and its strength characteristics ensure transportation, handling operations, and storage without destruction.

The compact from mixture 4 (see Fig. 2) during pressing had maximum strength with a change in final moisture content within 9–11% after drying. Thus, the binder composition of lignosulfonate and sugar (or molasses) solution provides high strength characteristics of the compacts.

Earlier, the authors developed a combined die consisting of two disks with flexible heating elements to regulate the mixture temperature in the channels of through-flow pressing [11]. The channels in the dies can be made either cylindrical or cylindrical-conical. Such a design makes this construction technologically feasible to manufacture.

The granulator operates as follows: as the rotating rollers move over the surface of the die, layer-by-layer and portion-wise pressing of the raw material into the channels occurs. As a result, at the outlet of the channels, cylindrical pellets are formed in the form of a solid porous body.

We consider the movement of the material in the cylindrical-conical channel and the equilibrium conditions of forces in the cylindrical channel of length h_{in} (see Fig. 3).

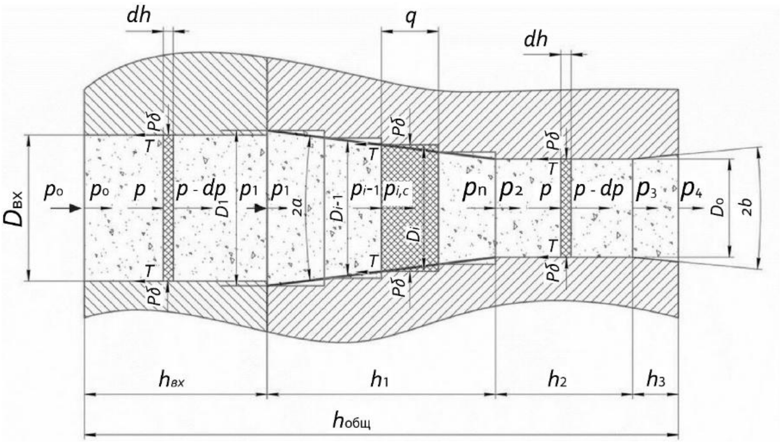


Fig. 3. Diagram of forces acting on the material in a through-flow pressing channel

Using the positive direction of the pressing forces for an element of length *dh* in different sections, we obtain the following equations for calculating the specific pressures in the cylindrical channel:

$$p\frac{\pi D_{in}^2}{4} - T = (p - dp)\frac{\pi D_{in}^2}{4}, \tag{1}$$

$$p_1 = p_0 \exp\left(-\frac{4}{D_{in}} f\xi h_{in}\right), \tag{2}$$

$$p_3 = p_2 \exp\left(-\frac{4}{D_0} f\xi h_3\right), \tag{3}$$

where p, p_0, p_1, p_2, p_3 are the pressure on the layer of the initial mixture, and at the inlet and outlet of each section, respectively; ξ is the coefficient of lateral pressure; f is the coefficient of external friction; T is the friction force; the remaining notations correspond to Fig. 3.

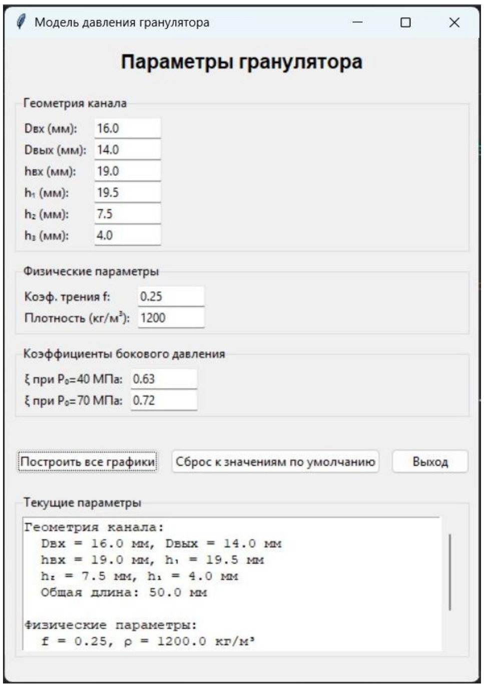
The specific pressure at the outlet of the conical part of the section is determined according to the expression

$$p_2 = p_n \frac{D_n^2}{D_0^2}, \tag{4}$$

where p_n is the pressure at the outlet of the last (n-th) element; D_n is the diameter of the last section.

When calculating the pressure distribution diagram along the channel length, the following values were adopted for the geometric dimensions of the channel: D_{in} = 8 mm; D_0 = 6 mm; h_{in} = 19 mm; h_1 = 19.5 mm; h_2 = 7.5 mm; h_3 = 4 mm; for the coefficient of external friction – f = 0.1. These values are determined by the die manufacturing technology. As the material under study for obtaining pellets, mixture 4 was selected (see Table 3).

At the exit of the material from the cylindrical-conical channel (length h_3), the compact expands under the action of elastic deformations, increases in size, and the pressure p_4 drops to zero. The Python programming language [12] was used to solve the system of pressure change equations (1)–(4) along the channel length, with the IDE PyCharm [13] as the development environment. The initial data entered included the granulator parameters, the geometric dimensions of the channel, the characteristics of the medium, and the operating parameters of the pressing process. The data entry menu is shown in Fig. 4.



Геометрия канала
Dвх (мм): 16.0
Dвых (мм): 14.0
hвх (мм): 19.0
h₁ (мм): 19.5
h₂ (мм): 7.5
h₃ (мм): 4.0

Физические параметры
Коэф. трения f: 0.25
Плотность (кг/м³): 1200

Коэффициенты бокового давления
ξ при P₀=40 МПа: 0.63
ξ при P₀=70 МПа: 0.72

Текущие параметры
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Геометрия канала:
  Dвх = 16.0 мм, Dвых = 14.0 мм
  hвх = 19.0 мм, h₁ = 19.5 мм
  h₂ = 7.5 мм, h₃ = 4.0 мм
  Общая длина: 50.0 мм

Физические параметры:
  f = 0.25, ρ = 1200.0 кг/м³
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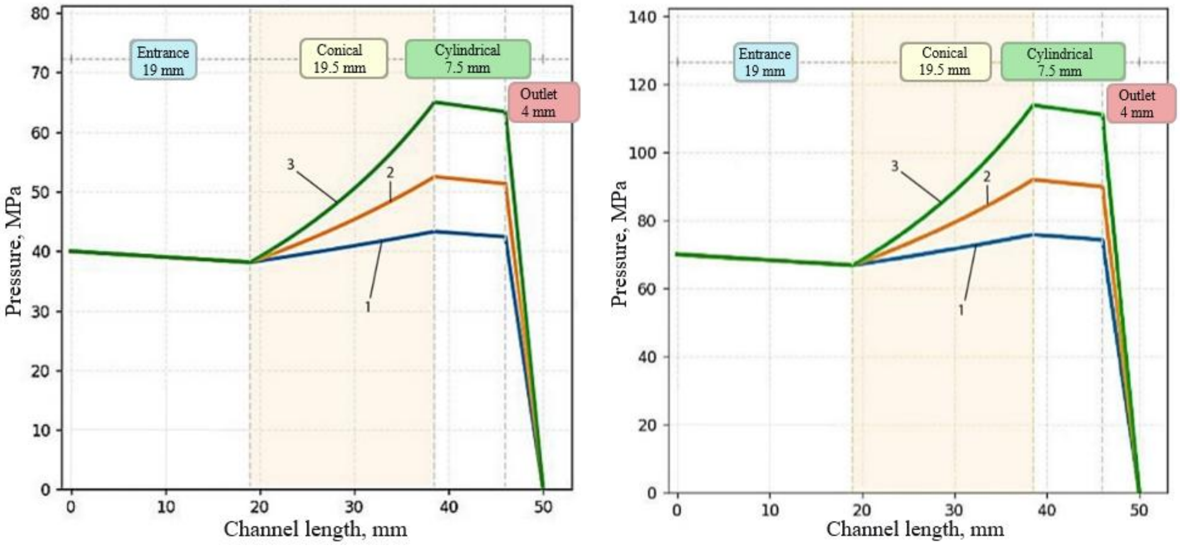
Fig. 4. Data entry menu in the PyCharm IDE environment

Using the obtained equations (2), (3), (4) with the corresponding values of the lateral pressure coefficient ξ for determining the pressure along the channel length (p_0, p_1, p_2, p_3), as well as the software, pressure distribution diagrams along the channel length were constructed. The influence of the cone angle and the initial pressing pressure were considered. According to Fig. 5, in the cylindrical part of the channel the pressure decreases from inlet to outlet; in the conical part it increases due to the rise in the lateral pressure coefficient. In sections h_2 and h_3, the pressure decreases due to the material exiting into the free space. Indeed, when the cone angle exceeds 3° over length h_1, the pressure increases, and plugs may form in the channel. It leads to a shutdown of the technological process.

The proposed method for calculating the force parameters in the channels of a flat die makes it possible to simulate the granulation process of brewing waste with different morphologies.



a) *b*)

Fig. 5. Pressure distribution diagrams in the cylindrical-conical channel of a flat die as a function of the cone angle 2α and the initial specific pressing pressure for mixture 4 at $\xi = 0.1$: (*a* – $p = 40$ MPa; *b* – $p = 70$ MPa): 1 – $\alpha = 1°$; 2 – $\alpha = 2°$; 3 – $\alpha = 3°$

Based on the conducted studies, the technological line for the production of a nutritive feed additive has been modernized, which can be used in animal husbandry. The granulation technology for BSG, implemented at Baltika Breweries LLC (Russia) was taken as a basis. A drawback of the existing scheme is the use of a bucket elevator for transferring the initial components from the contact dryer to the screw mixer. This results in the formation of spillage and product loss. This stage is accompanied by dust ingress into the workshop. It negatively affects the health of the personnel. Furthermore, the use of a rotary granulator with a ring die leads to dust formation and the generation of a fine off-spec fraction. In the proposed scheme, the bucket elevator is replaced by an enclosed belt conveyor equipped with local exhaust ventilation and a rotary granulator with a flat die used to reduce dust levels in the workshop.

A schematic diagram of the process for the utilization of BSG with kieselguhr using a rotary granulator with a flat die is shown in Fig. 6. Liquid BSG is fed into a storage hopper with a stirrer-homogenizer, from which it then flows into a decanter. After separation of the suspension, the separated free moisture is fed to a centrifuge, while the pressed spent grain is conveyed to a dryer. The filtrate leaving the decanter contains many suspended solids and organic substances (proteins, fiber, nitrogen-free extractives), so the resulting suspension is passed through a centrifuge. The clarified filtered liquid is discharged to the sewer.

At the inlet of the dryer, kieselguhr, pressed BSG, and the residue from the centrifuge are mixed. Drying is conducted by a contact method. The dried mixture enters a mixer; binders – molasses and technical lignosulfonate (the use of similar substitutes is possible) – are added to the charge. The mixture is transported to a rotary granulator with a flat die, developed at the NRC "Kurchatov Institute" (Moscow, Russia) [14]. In this granulator, rotating rollers force the charge through the die. The mixture, passing through the channels in the die, is pressed and emerges in the form of granules (pellets). These granules are conveyed by a belt conveyor to a cooler, where they are blown with air. To separate the commercial fraction, the product is separated. Granules with the sizes do not meet the specified requirements are returned to the screw mixer, while the commercial product is for packaging.

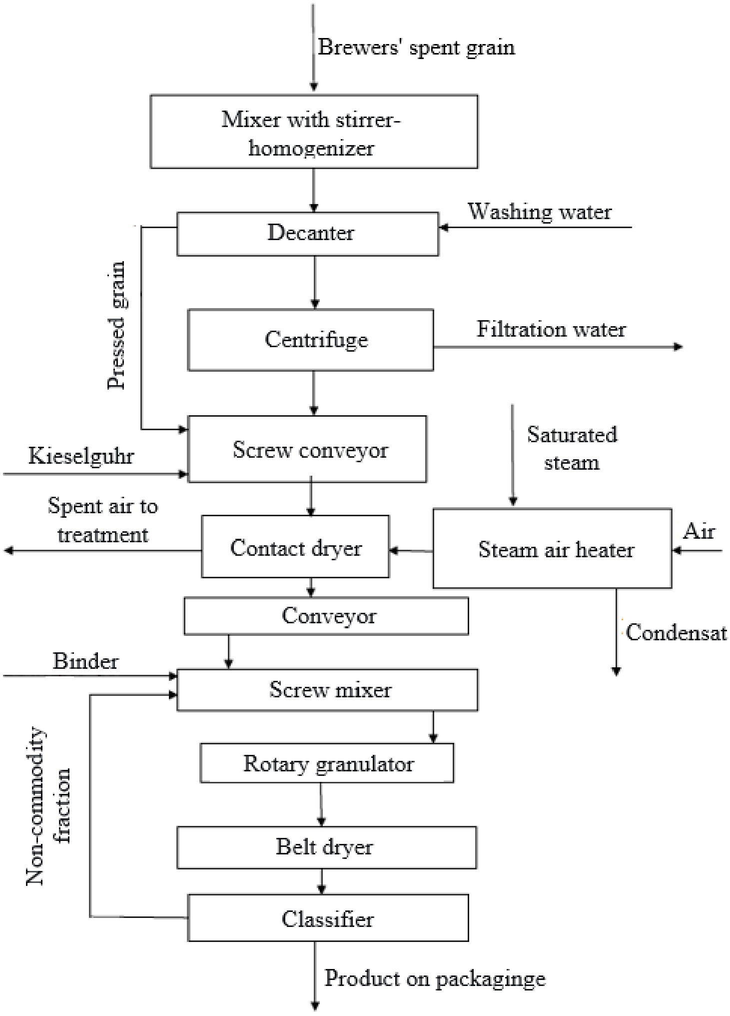


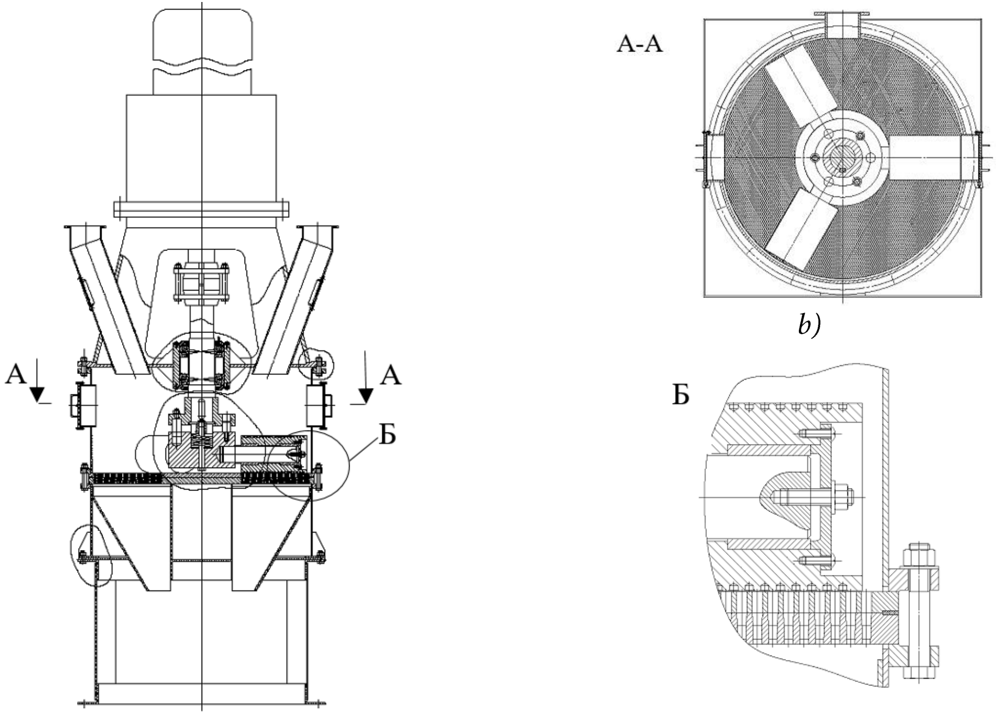
Fig. 6. Schematic diagram of the BSG utilization process with kieselguhr using a rotary granulator with a flat die

A distinctive feature of the developed rotary granulator with a flat die is the use of cylindrical-conical channels. It ensures the formation of cylindrical granules (pellets). Fig. 7 shows a general view of the developed granulator, which consists of an outer housing, powder feed nozzles, a flat die, and pressing rollers.

The prepared material (mixture of BSG, kieselguhr, and additives) is fed through the feed nozzles into the apparatus housing. The rotating rollers provide contact compressive stress on the material on the die, forcing it through the openings to obtain pellets at the die outlet. The material is supplied to the die and distributed over its entire surface by the rotating rollers.

The charge, entering under the pressing rollers, is pressed into the die channels. In the channels, the material is compacted and gradually forced through along the channel length.

In this design of a rotary granulator with a flat die, the principles of through-flow pressing are implemented. This type of pressing of bulk material is one-sided, since the movement of the punch occurs only relative to the die. The compacts exit from the bottom of the die. Compaction of the material occurs due to the narrowing of the die channel.



a) b) c)

Fig. 7. Diagram of a rotary granulator with a flat die: *a*) general view of the granulator; *b*) arrangement of the rolling rollers above the die; c) design of the flat die mounting in the housing

The length of the obtained granule is determined by the length of the outlet part of the forming channel. The resulting granules emerge from the outer side of the die, fall down an inclined chute into the hopper of a belt conveyor for packaging.

Conclusions

A description of the mechanism of granulation of BSG with kieselguhr in a cylindrical-conical channel of a flat die under the action of a pressing roller is proposed.

For the flat die, pressure distribution diagrams in the channel of variable cross-section have been constructed.

The compact from mixture 4 (see Table 3) has maximum strength when the final moisture content after drying is within 9–11%. Thus, the binder composition of lignosulfonate and sugar (or molasses) solution provides high strength characteristics of the compacts.

The optimal value is a density of ρ_{pr} = 1,000 kg/m^3. It corresponds to a change in the splitting tensile strength in the range of 0.2–0.8 MPa, achieved at a specific pressure of 80 MPa and moisture content of 7-10%.

Based on the results of experimental studies, a design of a rotary granulator with a flat die with cylindrical-conical channels has been developed.

An environmentally safe scheme for processing raw BSG and kieselguhr using a granulator with a flat die and new types of conveying devices has been proposed. The developed scheme for the utilization of brewing waste reduces the environmental burden on the environment.

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