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PRINCIPLES OF INNOVATIVE SEED PELLETING TECHNOLOGY

The increase in the world's population to 9 billion people is leading to an aggravation of the global food crisis. A key factor in solving this problem is the use of innovative technologies for preparing the seed fund, which will increase crop yields and consumer characteristics of the productive part of the harvest while rationally using the land fund of Ukraine, which is one of the five largest agricultural exporting countries.

An analytical review of the basic methods and equipment for processing crop seeds aimed at ensuring high yields, increasing resistance to adverse agroclimatic conditions and improving consumer characteristics of products is carried out. Existing methods of pre-sowing treatment include drying, coating, encrustment, and pelleting. These processes are usually carried out in bowl-type, drum-type, or stirrer machines. Despite their widespread use, they have a number of significant drawbacks. These include an increased risk of agglomerate formation, mechanical injury of the seeds, which reduces their germination, and low heat utilization, which affects the energy efficiency of the process.

To eliminate these shortcomings, an innovative seed treatment technology based on the use of an apparatus with a heterogeneous jet-pulsation mode of fluidization is proposed. This technology has a number of advantages, including reducing the risk of seed damage, ensuring uniform distribution of the coating, and a significantly higher coefficient of thermal utilization. The use of this technology allows for an efficient granulation process, which is especially important in the production of granular organic-mineral fertilizers. The research results show that the use of a fluidized bed apparatus contributes to the production of spherical granules with a layered structure. Such granules contain nutrient minerals, bone meal, and humic compounds that provide comprehensive plant nutrition. An important indicator of the process efficiency is the low dust emission factor of less than 12%. The thermal coefficient of the technology exceeds 50%, which indicates its high energy efficiency.

The proposed innovative technology has high adaptive properties for a full cycle of pre-sowing seed preparation, from drying, calibration and dressing to encrustment and pelleting. This allows us to achieve high results even in unfavorable agroclimatic conditions. Innovative solutions are based on the use of the original jet-pulsation fluidization mode, which allows to increase the efficiency of heat and mass transfer in combination with intensive renewal of the phase contact surface. Due to this technology, it is possible to carry out pre-sowing preparation according to an individual program, which will help to improve the consumer characteristics of agricultural products and preserve environmental balance.

Keywords: *pelleting, granulation, heterogeneous fluidization, jet-pulsation mode, volumetric mixing*

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Formulation of the problem. In modern conditions, pre-sowing seed treatment is increasingly used to ensure sustainable yields of agricultural products with high consumer qualities. In particular, according to [1, 2], high-quality seed preparation can lead to an increase in yields of up to 30 %. However, even in this case, without additional local protection and nutrition of each seed, the desired results cannot be achieved due to the influence of weather conditions and pathogenic microflora in the soil. Therefore, the first important step is seed treatment with special solutions for each crop [3].

The global market for seed coating materials (dyes, polymers, fillers, and other additives) was worth 1.8 billion USD in 2019 and is projected to reach 3.0 billion USD by 2025 [4]. The main group of active ingredients are chemical seed treatments, which are estimated to be worth between 3 and 5 billion USD in 2020, accounting for at least 2/3 of the total seed treatment market [5].

A wide range of materials are used for seed treatment and coating. These materials have been categorized according to their composition and origin as synthetic chemicals (SYN), natural products or derivatives of natural products (NP), biological agents (BIO), and minerals extracted from the earth (MIN) (Table 1) [6]. Among these categories, certain materials can be used for organic use and labeling, and materials approved by the US Organic Materials Review Institute (OMRI) [7] have been labeled as organic (OR).

Seed treatments can contain fungicides, insecticides, nematicides, and bactericides to control pathogens and pests during sowing [8, 9]. For seed dressing, water-based liquids containing colorants, dressing chemicals, surfactants for better dissolution of these compounds, and binders are used. (Table 1). Each group of material in the table classified by function and composition [6].

Table 1 – Seed treatment and coating materials grouped as active components, liquids and solid particulates*

Active Components	Liquids	Solid Particulates
Biostimulants - SYN, NP, BIO (OR) Plant nutrients - SYN, MIN (OR) Abiotic stress: Drought and Salinity - SYN, BIO (OR) Plant Protectants - SYN, NP, BIO, MIN (OR) Inoculants - BIO, MIN (OR)	Water colorants - SYN, NP (OR) Adjuvants - SYN (OR) Binders - Polyvinyl alcohol (PVOH) and Polyvinyl acetate (PVAc): SYN - Methyl cellulose: SYN - Carboxymethyl cellulose (CMC): SYN - Plant starches: NP (OR) - Gum Arabic: NP (OR)	Binders - Also, under Liquids - Soy flour: NP (OR) Fillers - Diatomaceous earth (DE): MIN (OR) - Limestone: MIN (OR) - Gypsum: MIN (OR) - Bentonite: MIN (OR) - Vermiculite: MIN (OR) - Talc: MIN (OR) - Zeolite: MIN (OR) - Silica: MIN (OR) - $BaSO_4$: MIN

*Abbreviations for material source/origin: Synthetic Chemicals — SYN, Natural products or derivatives — NP, Biologicals — BIO, Mineral — MIN, substances may be Organically approved — OR

Analysis of previous studies. The most typical devices for applying the liquid phase to the grain surface are shown in Fig. 1 [6, 10, 11, 12].

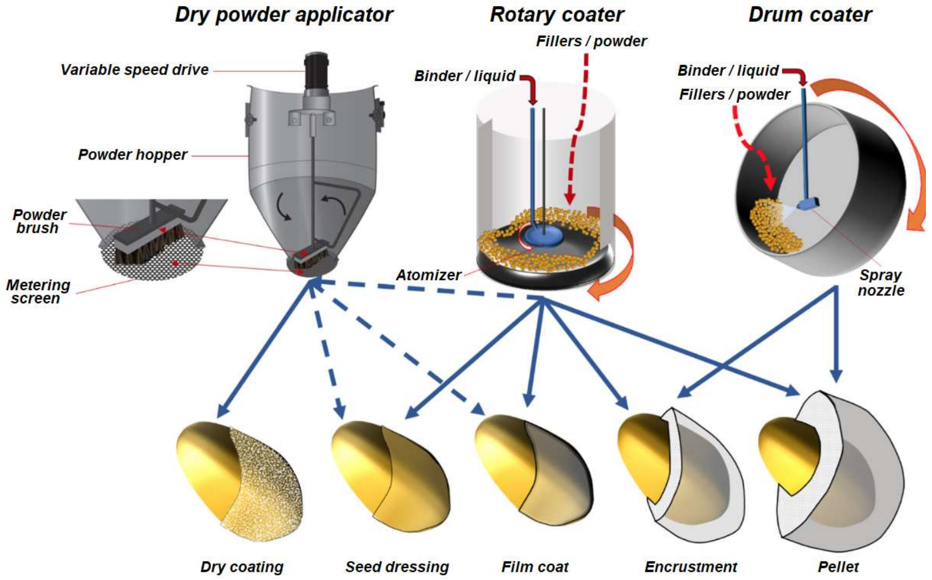


Fig. 1 – The three major types of seed coating equipment: dry powder applicator, rotary coater and drum coater used to produce five seed coatings: dry coating, seed dressing, film coat, encrustment and seed pellet

Dry powder coating is a seed coating method that involves mixing seeds with a dry powder used for fungal or bacterial treatment and then drying them [13, 14].
According to the authors of [6], the dosage of dry powders applied to seeds is limited by their adhesion to seeds and ranges from 0.06 to 1.0 % by weight of seeds (Fig. 2).

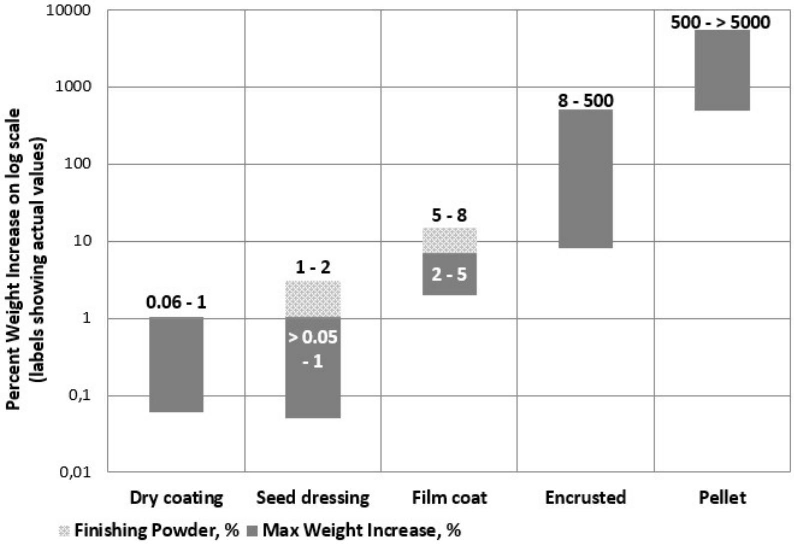


Fig. 2 – Percent weight increase after dry coating, seed dressing, film coat, encrustation and pellet seed technology [6]

The gray bar for seed dressing and film coating is the addition of finishing powder during the coating process. The percentage increase is shown on a logarithmic scale to facilitate comparison between technologies in Fig. 2.

In the work [6] is shown that the most common apparatus for all types of process (Fig. 1) is an apparatus with a stirrer in various modifications, in which the liquid and dust phases are sprayed using a mechanical disk-type disperser. In this case, due to the action of mechanical blades on the seeds, both the surface applied layer and the seeds themselves may be damaged. In addition, there is a high risk of agglomerate formation. To dry the resulting product, a drum machine is usually installed, or the process is carried out in a bowl granulator with subsequent drying of the material. Sometimes the pelletizing process is carried out in a cascade of drum machines (Fig. 3) [15].

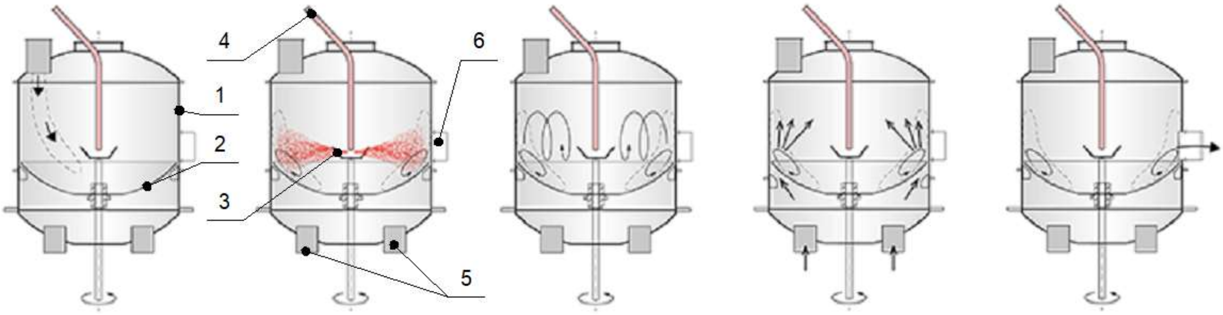
Fig. 3 – Pelletizing system DPP [15]

In the first drum, the product is irrigated with oil or other liquids, and in the second drum, it is mixed with bulk flavoring additives [15]. This technology is multi-stage with a low heat efficiency.

The company *Petkus/Roeber* [16] proposed a new multi-coater containing a rotating bottom filled with granular material, which rotates in the middle of a cylindrical apparatus, and the liquid phase is sprayed by a mechanical disperser into the middle of the rotating bottom, shown in Fig. 4.

Fig. 4 – Photo of the multi-coater *Petkus/Roeber* rotating bowl [16]

To reduce the risk of seed injury in these machines, which contain a rotating bottom, the seeds are supported on a pneumatic cushion [17]. This apparatus is batch and has the following stages, shown in Fig. 5.



a) filling *b) spraying* *c) mixing* *d) drying* *e) unloading of finished products*

1 – cylindrical body; 2 – rotating bottom; 3 – mechanical disperser; 4 – liquid phase supply pipe; 5 – diffusers for air supply; 6 – nozzle for unloading the finished product

Fig. 5 – The principle of *Petkus/Roeber* multi-coater functioning [17]

The cylindrical body of the apparatus 1 and the rotating bottom 2 are made of mirror-smooth stainless steel with electrolytic polishing to avoid sticking of liquid products. The stirrer has a special streamlined shape and an adjustable gap between the wall of the apparatus and the rotating bottom, and air is supplied through diffusers 5.

The obvious complexity of the design and the high cost of the manufacturing technology do not reduce the risk of seed injury in the gap between the edges of the rotating bottom and the walls of the cylindrical body. In addition, insufficient mixing does not ensure effective contact of the coolant with individual particles, which significantly reduces the mass and heat transfer coefficients. As a result, the specified coating uniformity is not ensured, the granular material is not dried sufficiently, and agglomerates spontaneously form during the pelletizing process.

The purpose of the article is to provide scientific substantiation of the use of innovative technology for the processes of encrustation and pelletizing of agricultural crop seeds using a heterogeneous jet-pulsation mode of fluidization.

The scientific novelty lies in the interaction of the gas coolant with the granular material in the apparatus by introducing two jets in orthogonal planes into the lower part of the granulator, which, after combining, create a cyclic jet-pulsation mode of fluidization, accompanied by removal to the space above the initial bed and return to the initial state of about 40 % of the mass of the initial bed with a frequency of 1.7–2.7 Hz.

Presentation of the main material. The peculiarity of the pelletizing process is the formation of a multilayer cluster on the surface of the grain, which is 5 or more times its initial mass. At the same time, the pelletized seed is a biological object with a specific genetic code and, when applied to the soil, must be active and have the resource to counteract negative factors of organic, chemical and climatic origin.

Technologically, the pelletizing process involves the cyclical application of a liquid phase containing a solvent, mineral and organic nutrients, and growth stimulants to the seed surface, followed by evaporation of the solvent (water). As a result, a composite solid phase with a micro-layer structure is formed on the seed surface. To do this, it is necessary to ensure effective circulation of the granular material between the irrigation and drying zones without mechanical damage to the seeds. But the main feature is that the process can only take place at a temperature of 40 ºC, and the heat supply for the evaporation of the solvent from the liquid formed on the grain surface can only be due to convection from the heated coolant.

Given that the heat transfer coefficient α from the gas coolant has a limited value, an increase in the amount of heat supplied can be achieved by increasing the total contact surface of the phases F, i.e., the product αF tends to *max*. Considering that the liquid phase is continuously dispersed into the fluidized bed, to ensure stable kinetics of the process with a layer-by-layer granulation mechanism, it is necessary to actively renew the working surface of the phases in the irrigation and drying zones at a high driving force for mass transfer. This will increase the coefficient of utilization of the supplied heat with the heated coolant.

All of these requirements are met by a fluidized bed apparatus, in which a continuous gas medium is used as a liquefying agent, heat carrier, and moisture-receiving phase. It is known that the coefficient of utilization of the supplied heat of such an apparatus can reach 50 % or more, and in the case of heterogeneous fluidization, the coefficients of heat and mass transfer increase by 1.5–2 times [18]. High efficiency of the transfer processes in a fluidized bed apparatus is achieved through the use of a heterogeneous jet-pulsation hydrodynamic regime, the physical model of which is shown in stages in Fig. 6 [19].

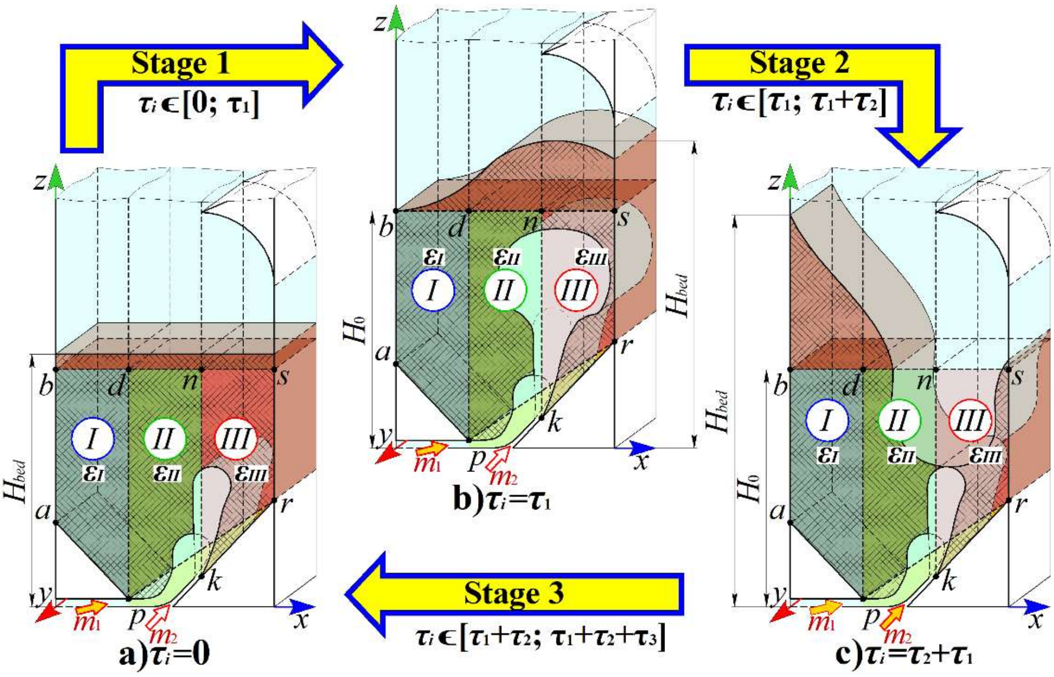


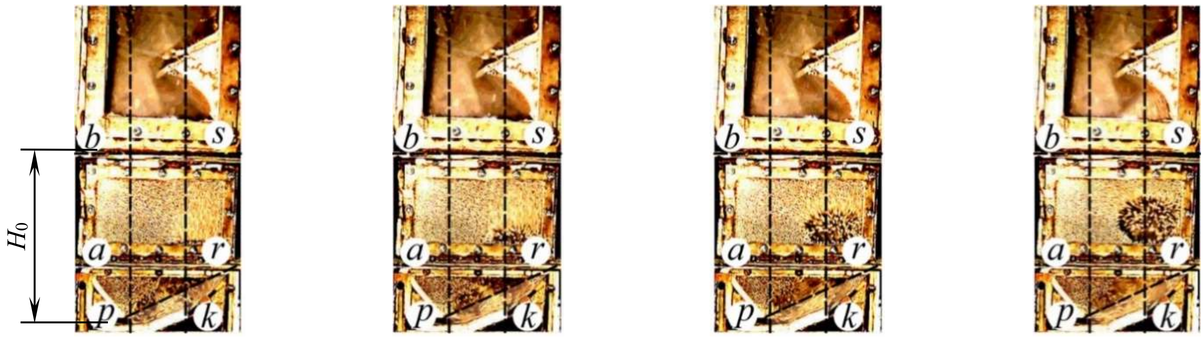
Fig. 6 – Stages of evolution of inhomogeneous jet-pulsation fluidization [19]

At the first stage of the cycle (induction period), during time τ_1 a gas bubble is formed at a height $z_f + \Delta$ (Fig. 6 *b*) and reaches its critical size. The second stage (τ_2) is the pulsatile ejection of a significant mass of granular material from zones *III* and *II* into the space above the initial bed and its movement to zone *I* (Fig. 6 *c*) by one or more bubbles until the residual height of the granular material in zone *III* $H_{res.(III)} \leq z_f + \Delta$. Then there is an intensive movement of the bed of granular material from the space above the initial bed of zone *I* into the formed voids in zones *II* and *III* , and the system returns to the initial state of equilibrium (Fig. 6 *a*) with the countercurrent movement of the solid and gas phases (stage 3) – (τ_3). That is, the duration of one cycle of pulsations is, s: $\tau_c = \tau_1 + \tau_2 + \tau_3$ [19].

Such a hydrodynamic regime is characterized by a nonlinear change in the bed height to $(1.7 \div 2.0)H_0$ in zone *I* and the heterogeneity of its porosity (in a fixed volume *absrkp*), which in zone *I* remains constant $\varepsilon_I = \varepsilon_0 = 0.4$, and in zones *II* and *III* can cyclically change from $\varepsilon_{II(min)}$ to $\varepsilon_{II(max)} = 1.5\varepsilon_0$ and from $\varepsilon_{III(min)}$ to $\varepsilon_{III(max)} = 2\varepsilon_0$. For flat slots of gas distribution device, the size of the gas bubble is determined by equation (1) and in the case of a decrease in the height of the granular material at the boundary of zones *II* and *III* the size of the bubble will adequately decrease as the height of the residual bed of solids in the zone of the vertical jet decreases (Fig. 6).

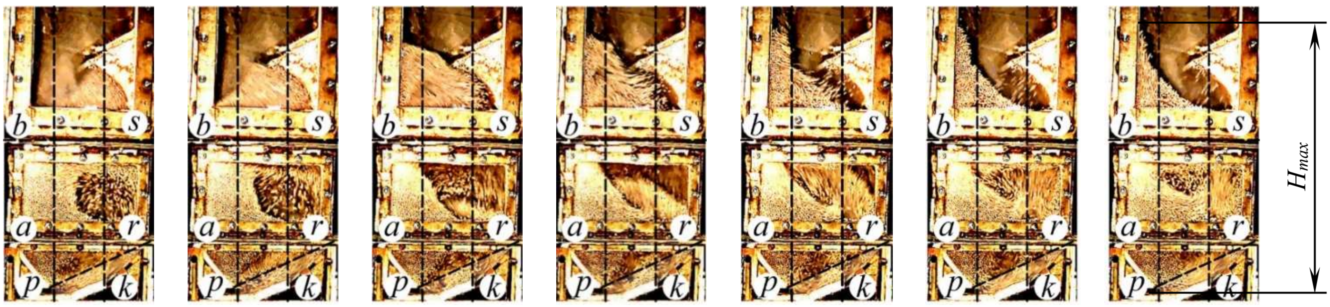
$$d_b = 4\,(H_0 - z_f - \Delta)\,/\,(4 + \pi). \qquad (1)$$

The experimental studies conducted by the authors of [20], shown in Fig. 7–9, confirm the provisions of the physical model of the jet-pulsation fluidization with a pulsation frequency of 1.7 Hz when using granular organic-mineral fertilizers with a diameter 4 mm, a density 1450 kg/m^3 at a height of the initial (stationary) bed $H_0 = 0.32$ m. Hydrodynamics studies were conducted on a pilot installation with a granulator chamber size of $A \times B \times H = 0.3 \times 0.1 \times 1.5$ m [20]. Photographic fixation of the state of the bed of granular material at the first, second, and third stages of the cycle at $d_e = 4.0$ mm; $K_w = 1.43$; $w_{g(bed)} = 1.64$ m/s; $w_{g(slits)} = 36.6$ m/s) is shown in Fig. 7–9.



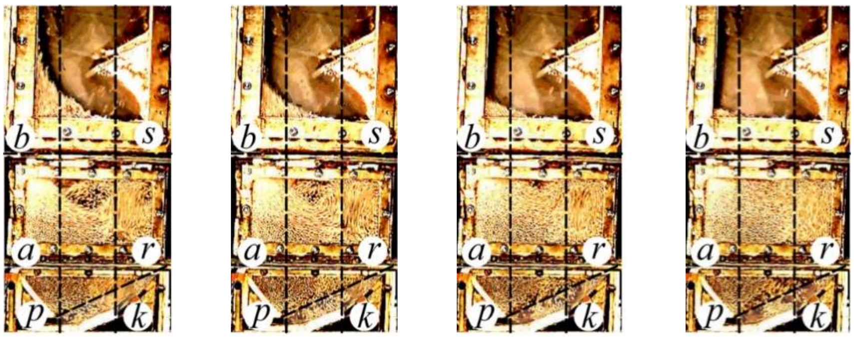
a) $\tau = 0.00$ *s* *b*) $\tau = 0.04$ *s* *c*) $\tau = 0.08$ *s* *d*) $\tau = 0.12$ *s*

Fig. 7 – Photo fixation of the state of the fluidized bed at the first stage of the cycle $0 \leq \tau \leq 0.12$ s



a) $\tau = 0.16$ *s* *b*) $\tau = 0.20$ *s* *c*) $\tau = 0.24$ *s* *d*) $\tau = 0.28$ *s* *e*) $\tau = 0.32$ *s* *f*) $\tau = 0.36$ *s* *g*) $\tau = 0.40$ *s*

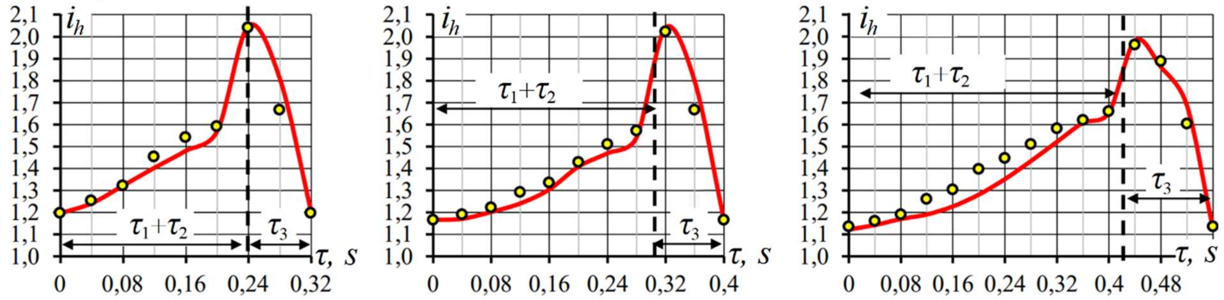
Fig. 8 – Photo fixation of the state of the fluidized bed at the second stage of the cycle $0.16 \leq \tau \leq 0.40$ s



a) $\tau = 0.44$ *s* *b)* $\tau = 0.48$ *s* *c)* $\tau = 0.52$ *s* *d)* $\tau = 0.56$ *s*

Fig. 9 – Photo fixation of the state of the fluidized bed at the third stage of the cycle $0.44 \le \tau \le 0.56$ s

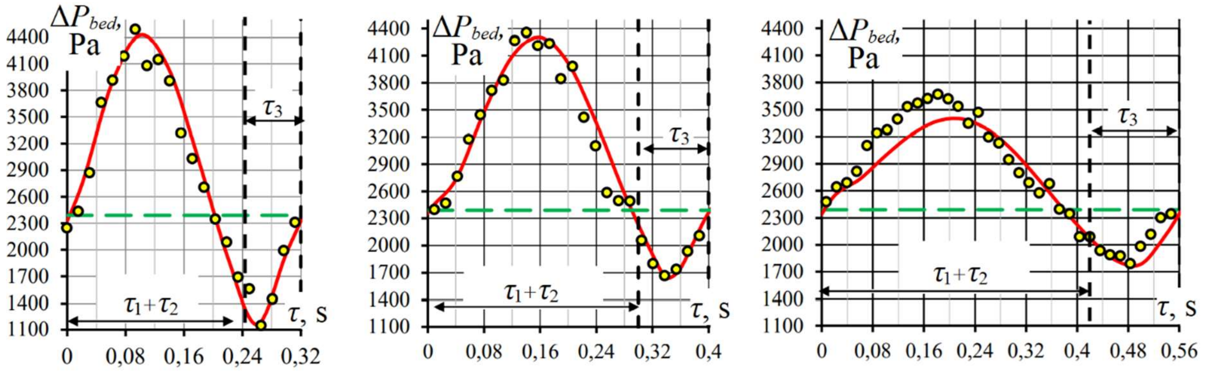
The results of the experimental studies were summarized in the form of indices of increasing the total height of the bed of granular material $H_{bed}/H_0 = i_h$, $H_{bed}/H_0 = f(\tau)$ and $\Delta P_L = f(\tau)$. The dynamics of changes in these parameters in one cycle is shown in Fig. 10–11 [19]. Thus, the maximum value $i_{h(max)} = 2$ is achieved for pellet diameters $d_e = (1.5–4.0$ mm), and the duration of one cycle adequately increases from 0.32 to 0.56 s, corresponding to a pulsation frequency $f = 1.7–2.7$ Hz (Fig. 10). Moreover, this result is achieved at higher values of the fluidization number for smaller pellet diameters, which is very important for minimizing the risk of agglomeration and maintaining the driving force for heat and mass transfer.



a) $d_e = 1.5$ mm; $K_w = 2.66$ *b)* $d_e = 2.5$ mm; $K_w = 2.03$ *c)* $d_e = 4.0$ mm; $K_w = 1.43$

Fig. 10 – Dynamics of changes in the index of increase in the total bed height at $H_0 = 0.32$ m or different values of d_e [19]

The results of monitoring the pressure drop across the fluidized bed during one cycle are shown in Fig. 11 [19].



a) $d_e = 1.5$ mm; $K_w = 2.66$ *b)* $d_e = 2.5$ mm; $K_w = 2.03$ *c)* $d_e = 4.0$ mm; $K_w = 1.43$

Fig. 11 – Dynamics of changes in the pressure drop in the bed of granular material at $H_0 = 0.32$ m for different values of d_e [19]

This made it possible to calculate the dynamics of changes in the mass of granular material in the initial geometric volume of the bed, shown in Fig. 12.

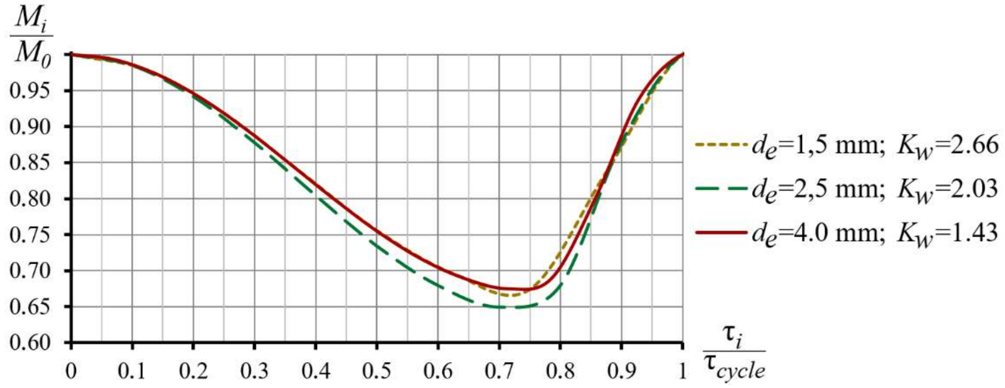
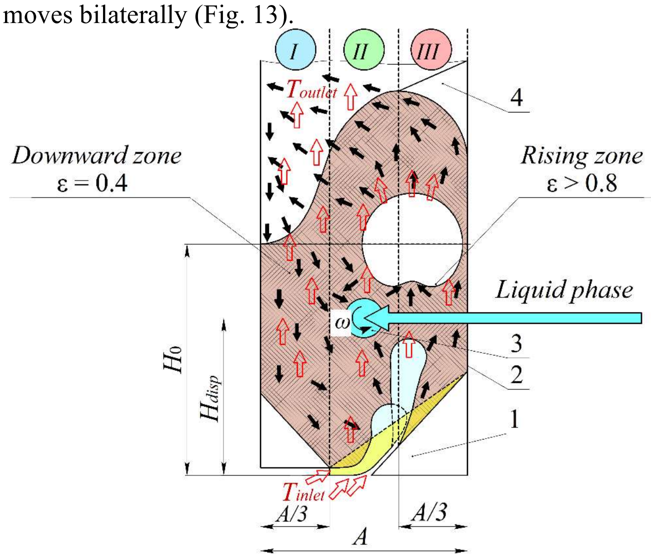


Fig. 12 – Dynamics of the change in the mass of the fluidized bed in the initial volume of the bed for particles with different values of the diameter d_e at different fluidization rates K_w

Therefore, regardless of the size of the particles, the removal of material outside the initial bed of solids is achieved by removing more than 30 % of the initial mass of the fluidized bed not only in a strictly vertical direction in the bed, but also in a transverse horizontal direction in the space above initial bed. Moreover, for 2/3 of the cycle, the material is carried out from the initial volume of the fluidized bed to the space above the initial bed (forward flow), in the center of which the mechanical disperser of the liquid phase is located, while 1/3 of the cycle the transferred material moves in the opposite direction (counterflow) (Fig. 13). Given this time ratio, the particle velocity in the counterflow movement is on average 2 times higher than in the forward flow. This leads to the turbulization of the boundary hydraulic sublayer around the solid particles, which significantly reduces the diffusion resistance to mass transfer. That is, in three cycles, there is a high probability of achieving a complete renewal of the entire working surface of the bed of granular material in the granulator chamber due to volumetric 3D mixing.

The essence of the process of the proposed technology is that seeds are loaded into the chamber of the granulator 2, which has the shape of a parallelepiped, equipped in the lower part with a gas distribution device 1 (GDD) (Fig. 13). The heated coolant is introduced asymmetrically into the apparatus through the GDD to create a jet-pulsation fluidization. The liquid phase is sprayed by a mechanical disperser 3 located inside zone *II*, through which the mass of granular material moves bilaterally (Fig. 13).



1 – gas distribution device, 2 – granulator chamber, 3 – mechanical disperser, 4 – directing distributor;

Fig. 13 – Scheme of the apparatus for carrying out the process of pelleting and granulation under inhomogeneous fluidization

Testing of this technology in the dehydration and granulation of heterogeneous liquid systems containing almost the same amount of bone meal 29 % (organic matter) and ammonium sulfate 27 % (mineral component), 2 % each of potassium chloride and humate, made it possible to obtain organic-mineral fertilizers of stimulating action (Fig. 14) of spherical shape with a layered structure (Fig. 15) [18].

Fig. 14 – General view of humic-phosphorus-calcium-nitrogen-potassium-sulfur-containing fertilizers with a stimulating effect of the composition:
$\mathit{Г} : \mathit{P} : \mathit{Ca} : \mathit{N} : \mathit{K} : \mathit{S} = 1 : 10 : 19 : 11 : 2 : 12.5$

1 – initial center of granulation,
2 – layered structure;

Fig. 15 – Cross-section of the pellet (increased by a factor of 10)

At the same time, the granulation coefficient $\Psi \geq 88$ % (dust removal less than 12 %) with a specific moisture load of the bed surface a_f = 0.51 kg/(m^2·h), which is 2 times higher than this parameter compared to the process when implementing homogeneous fluidization [18].

Conclusions. An innovative technology of pelletizing with the use of heterogeneous jet-pulsation fluidization has been substantiated and successfully tested for the production of granular organic-mineral fertilizers during the dehydration of composite fertilizers containing nutrients of mineral and organic origin and stimulating macro-impurities. The weight of the final granular product increased by 18 times compared to the initial one without deterioration of physical, meso-mechanical and chemical properties, which indicates the high adaptability of the proposed technology. The fundamental difference from existing technologies is the possibility of obtaining a layered structure on the surface of seeds according to an individual recipe, which is determined by the agro-climatic and environmental conditions of the region of application.

In addition, the proposed technology is also quite suitable for efficient drying, dressing, encrustment and even calibration.

Prospects for further research. Further research will be aimed at determining the features of hydrodynamics for each type of seed, taking into account their aerodynamic properties and conditions of pelletizing processes that ensure the preservation of high biological activity of treated seeds.

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ЗАСАДИ ІННОВАЦІЙНОЇ ТЕХНОЛОГІЇ ДРАЖУВАННЯ НАСІННЯ

Збільшення чисельності населення на планеті до 9 млрд осіб приводить до загострення світової продовольчої кризи. Ключовим фактором у вирішенні цієї проблеми є застосування інноваційних технологій підготовки насіннєвого фонду, що дозволить підвищити врожайність сільгоспкультур і споживчі характеристики продуктивної частини урожаю при раціональному використанні земельного фонду України, яка входить до п'ятірки найбільших країн-експортерів сільськогосподарської продукції.

Проведено аналітичний огляд базових методів та обладнання для обробки насіння сільськогосподарських культур, які спрямовані на забезпечення високої врожайності, підвищення стійкості до несприятливих агрокліматичних умов та покращення споживчих характеристик продукції. Існуючі методи передпосівної обробки включають процеси сушіння, протруювання, інкрустації та дражування. Ці процеси зазвичай проводяться в апаратах чашового, барабанного типу або в апаратах з мішалками. Незважаючи на їх широке застосування, вони мають низку значних недоліків. До таких належать підвищений ризик утворення агломератів, механічне травмування насіння, що знижує його схожість, а також низький коефіцієнт використання теплоти, що впливає на енергоефективність процесу.

Для усунення зазначених недоліків запропоновано інноваційну технологію обробки насіння, яка базується на використанні апарату з неоднорідним струменево-пульсаційним режимом псевдозрідження. Ця технологія має низку переваг, серед яких зниження ризиків пошкодження насіння, забезпечення рівномірного розподілу покриття, а також значно вищий коефіцієнт теплового використання. Застосування цієї технології дозволяє ефективно здійснювати процес грануляції, що особливо важливо при виробництві гранульованих органо-мінеральних добрив. Результати досліджень свідчать, що використання апарату з псевдозрідженим шаром сприяє одержанню гранул сферичної форми з пошаровою структурою. До складу таких гранул входять поживні мінеральні речовини, кістяне борошно та гумінові сполуки, які забезпечують комплексне живлення рослин. Важливим показником ефективності процесу є низький коефіцієнт пилевинесення, що становить менше 12 %. Термічний коефіцієнт технології перевищує 50%, що свідчить про її високу енергоефективність.

Запропонована інноваційна технологія має високі адаптивні властивості для проведення повного циклу передпосівної підготовки насіння від сушіння, калібрування і протруювання до інкрустації та дражування. Це дозволить досягати високих результатів навіть за несприятливих агрокліматичних умов. Інноваційні рішення ґрунтуються на використанні оригінального струменево-пульсаційного режиму псевдозрідження, що дозволяє підвищити ефективність тепломасообміну в поєднанні з інтенсивним оновленням поверхні контакту фаз. Завдяки цій технології можливе проведення передпосівної підготовки за індивідуальною програмою, що сприятиме підвищенню споживчих характеристик сільськогосподарської продукції та збереженням екологічної рівноваги.

Ключові слова: *дражування, грануляція, неоднорідне псевдозрідження, струменево-пульсаційний режим, об'ємне перемішування*

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