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Principles of Innovative Technology for Presowing Seed Treatment

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Abstract: The results of studies on an innovative technology for complex presowing seed treatment, which includes the application of protective and nutrient substances with subsequent drying, are presented. Traditional apparatuses with mechanical agitators or rotating bottoms have substantial limitations, such as a high risk of mechanical damage to seeds, the formation of agglomerates, and a low intensity of heat and mass transfer. To solve these problems, the application of an inhomogeneous jet-pulsating fluidization in a self-oscillating mode is put forward as a viable solution. A physical model of the interaction of a gas coolant with granular material of non-spherical (ellipsoidal) shape is theoretically and experimentally validated using wheat grains as an example. It has been experimentally proven that in a gas flow, seeds orient themselves with minimal projection along the flow direction. This reduces hydrodynamic resistance and leads to a local increase in bed porosity to 0.5-0.9. It was established that the introduction of a coolant forms an intense asymmetric spouting motion. At the same time, cyclic entrainment of about 40 % of the bed mass into the freeboard space occurs with a frequency of more than 1.5 hertz. The ratio of the gas bubble volume to the initial bed volume increases to 37 %. This specific hydrodynamic condition provides active volumetric mixing with a significant increase in the interfacial contact area and intensification of heat and mass transfer processes at low temperatures (not exceeding 40 °C), which significantly mitigates the risk of thermal degradation and mechanical impact to the seeds compared to traditional methods.

Index Terms: Presowing Seed Treatment, Fluidized Bed, Jet-Pulsating Fluidization, Heat and Mass Transfer, Granular Material, Seed Coating

1. Introduction

In the contemporary agricultural landscape, presowing seed treatment is increasingly used to ensure stable yields of agricultural products with high consumer qualities. In particular, according to [[1], [2]] high-quality seed preparation is projected to enhance yields of up to 30%. However, even in this case, without additional local protection and nutrition for each seed, target yields remain unattainable due to the influence of weather conditions and pathogenic microflora in the soil. Therefore, the first important stage is the treatment of seeds with specific solutions for each crop [[3]].

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The global market for seed coating materials (colorants, polymers, fillers, and other additives) was valued at USD 1.8 billion in 2019 and is projected to reach USD 3.0 billion by 2025 [[4]]. The main group of active substances includes chemical seed treatments, the value of which was estimated at USD 3 to 5 billion in 2020, accounting for at least 2/3 of the entire seed treatment market [[5]].

A wide range of materials is used for seed treatment and coating. These materials have been classified by their composition and origin as synthetic chemicals (SYN), natural products or derivatives of natural products (NP), biological agents (BIO), and mined minerals (MIN) [[6]]. Among these categories, certain materials can be used for organic applications and labeling, and materials approved by the Organic Materials Review Institute (OMRI) [[7]] have been designated as organic (OR).

Seed treatments may contain fungicides, insecticides, nematicides, and bactericides to control pathogens and pests during sowing [[8]]. Water-based liquids containing colorants, treating chemicals, surfactants for better dissolution of these compounds, and binders are used for the treatment [[9]].

2. Literature Review

The most typical apparatuses for applying the liquid phase to the surface of grains are shown in Fig. 1. [[10]].

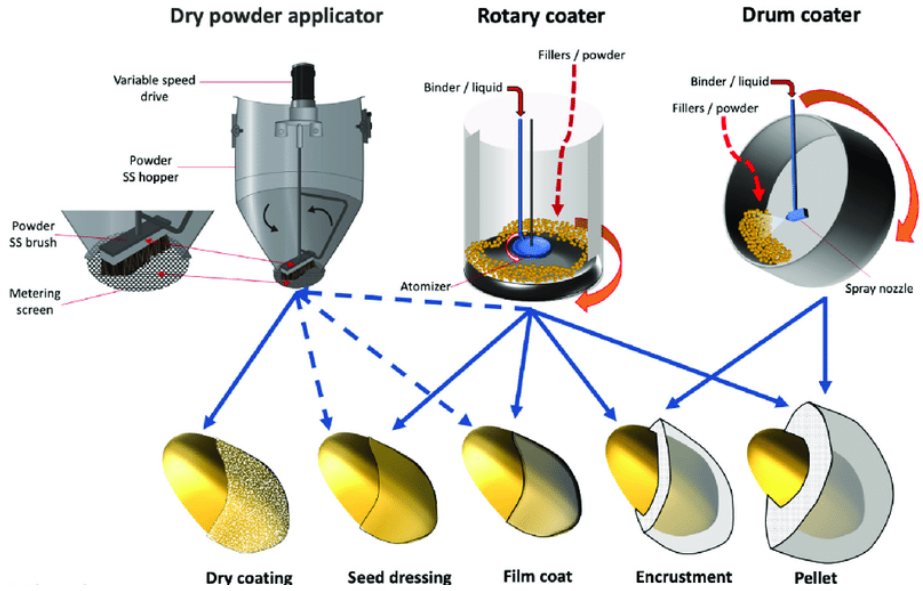


Fig. 1. Typical apparatuses for applying the liquid phase to the surface of grains [[10]]

It was shown in [[9], [11]] that the most common apparatuses for all types of the process, Fig. 1, are agitator-equipped devices in various modifications, in which the liquid and dust-like phases are sprayed using a mechanical disc-type disperser. In this case, due to the action of mechanical blades on the seeds, damage to both the applied surface layer and the seeds themselves is possible. In addition, there is a high risk of agglomerate formation. To dry the resulting product, a drum-type apparatus is usually installed, or the process is carried out in a pan granulator with subsequent drying of the material [[9]]. This method is characterized by a low heat utilization coefficient and a low evaporation capacity.

The *Petkus/Roeber* company [[11]] proposed a new multi-treater containing a rotating bottom filled with granular material, which rotates inside a cylindrical apparatus, while the liquid phase is sprayed by a mechanical disperser into the center of the rotating bottom, Fig. 2.

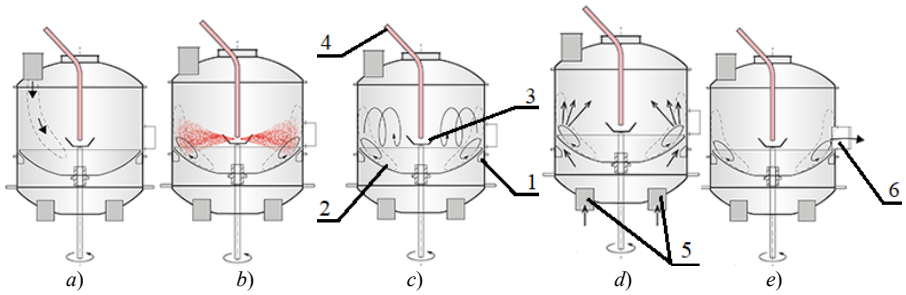


Fig. 2. Photo of rotating bowl multi-coater *Petkus/Roeber* [[11]]

To reduce the risk of seed damage in apparatuses containing a rotating bottom, the seeds are supported by an air cushion [[12]]. This is a batch apparatus, and the process occurs in 5 stages, Fig. 3.

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

The inherent structural complexity of the design and the high cost of the manufacturing technology do not reduce the risk of seed damage in the gap between the edges of the rotating bottom and the walls of the cylindrical body. In addition, due to insufficient mixing, effective contact of the coolant with individual particles is not ensured, which significantly reduces the heat and mass transfer coefficients. As a result, the specified coating uniformity is not ensured, the granular material is insufficiently dried, and agglomerates form unpredictably during the pelleting processes.



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 – air diffusers; 6 – finished product discharge pipe

Fig. 3. The principle of operation of the *Petkus/Roeber* multi-drag machine [[12]]

The aim of the research is to scientifically substantiate the principles of an innovative technology for complex presowing seed treatment using an inhomogeneous jet-pulsating fluidization mode for non-spherical granular material.

Modern approaches to presowing treatment increasingly emphasize the use of bottom-sprayed fluidized bed coaters to optimize the uniformity of functional polymer layers, such as alginates, on agricultural seeds [[13]]. It is well-documented that strict adherence to optimal thermal modes directly influences not only the viability of the seed embryo during priming and coating but also the overall fluidization state of the bed [[14]].

This research presents a novel approach to the interaction of the gas coolant with non-spherical granular material in the apparatus chamber by introducing the gas flow into the lower part of the granulator as two jets in orthogonal planes. After merging, the jets create a cyclic jet-pulsating fluidization mode, which is accompanied by the entrainment of about 40% of the initial bed mass into the freeboard space and its return to the initial state at a frequency of more than 1.5 Hz, significantly increasing the intensity of heat and mass transfer processes.

3. Physical Model of Presowing Seed Treatment in a Fluidized Bed

Presowing seed treatment is a technological process involving the cyclic sizing, drying, and application of a liquid phase (fungicides, nutrients, and growth stimulators) onto the seed surface, followed by the evaporation of the solvent (water). As a result, a composite solid phase with a micro-layered structure forms on the seed surface. For the effective progression of the process, it is necessary to ensure active volumetric mixing of the granular material in the apparatus chamber and intense circulation between the wetting and drying zones without causing mechanical damage.

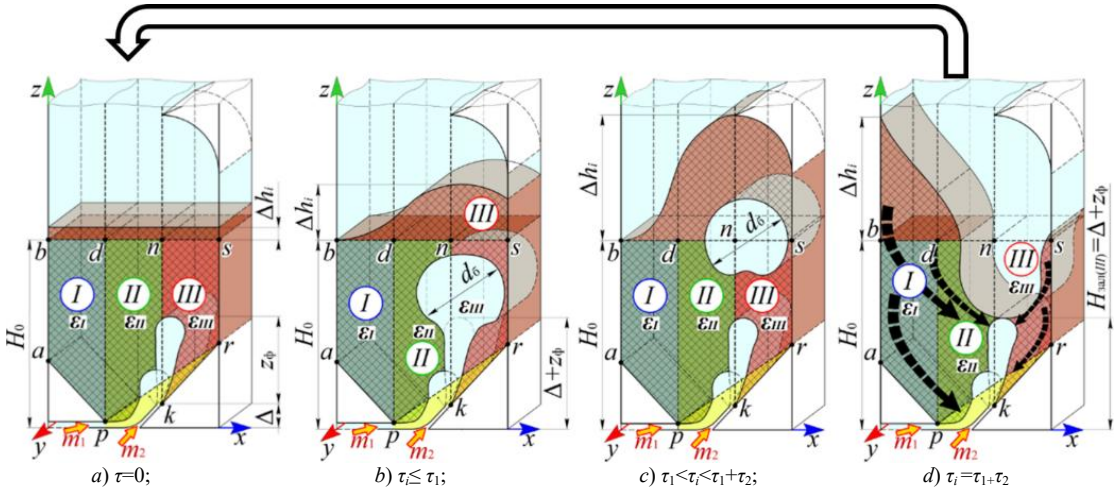
Since seeds are biological objects, dehydration is only possible at a temperature not exceeding 40 °C with maximum heat supply from the gas coolant to the surface of the moistened seed. Given the limited value of the heat transfer coefficient, an increase in the supplied heat is achieved by increasing the total interfacial contact area F_{MT}, i.e., maximizing the product αF. The continuous injection of the liquid phase into the fluidized bed requires active renewal of the working interfacial contact area in the wetting and drying zones under a high mass transfer driving force, which ensures the efficient use of the supplied heat.

These requirements are met by a fluidized bed apparatus, in which the gas acts as a fluidizing agent, a coolant, and a moisture carrier. The heat utilization coefficient can exceed 50%, and with the application of inhomogeneous fluidization, the heat and mass transfer coefficients increase by 1.5–2 times [[15]]. The high efficiency of transfer processes in a fluidized bed apparatus is achieved through the application of an inhomogeneous jet-pulsating hydrodynamic mode.

Fig. 4. [[16]] shows the physical model of jet-pulsating fluidization for spherical material. In this mode, over 40% of the initial bed material is entrained beyond the initial volume (the boundary is the line *bdns*, Fig. 4., at a frequency of up to 2 Hz, and the specific moisture load during the production of organo-mineral fertilizers increases twofold.

The technical concept of implementing the jet-pulsating mode is that a horizontal jet from a slit (dot *p*, Fig. 4*a.*) is directed toward a slit (dot *k*, Fig. 4*a.*), from which a vertical jet of height z_f is formed. As a result, a gas bubble forms at the top of the vertical spout, beginning to displace solid particles outside the initial bed volume in the apparatus chamber,

Fig. 4*b*. This static displacement of the material reaches its maximum and transitions into dynamic entrainment of the material into the freeboard space at the moment the bubble detaches from the spout, Fig. 4*c*. The entrained material, after contacting the deflector insert, moves to zone *I*, Fig. 4*d*. Thus, voids are formed in zones *III* and *II* which are intensively filled due to the movement of material from zone *I*, Fig. 4*d., e*.



a) τ=0; *b*) $\tau_i \leq \tau_1$; *c*) $\tau_1<\tau_i<\tau_1+\tau_2$; *d*) $\tau_i=\tau_1+\tau_2$

Fig.4. The method of interaction of gas and solid phases in the granulator chamber during inhomogeneous fluidization in the self-oscillating mode (one cycle) [[16]]

A specific feature of the process is the creation of a gas bubble that acts as an accumulator of potential energy. Therefore, at the moment of detachment of a gas bubble with diameter d_{bubble}, the lifting force is calculated by the expression, N:

$$O=\frac{1}{6}\pi {d_{bubble}}^3 \rho_{solids}(1-\varepsilon_0)g \quad (1)$$

Where:

- ρ_{solids}: Density of solid particles, kg/m
- ε_0: Porosity of a bed of solids at rest
- g: Acceleration due to gravity, m/s²

The hydraulic resistance of the bed at the moment of gas bubble formation will increase by the value, Pa:

$$\Delta P_b=\frac{O}{S_a} \quad (2)$$

Where:

- S_a: Cross-sectional area of the apparatus chamber, m^2

Then the total increase in the hydraulic resistance of the bed at this moment will be, Pa:

$$\Delta P=\Delta P_{nom}-\Delta P_b \quad (3)$$

Where:

- ΔP_{nom}: Nominal pressure drop at minimum fluidization velocity, Pa

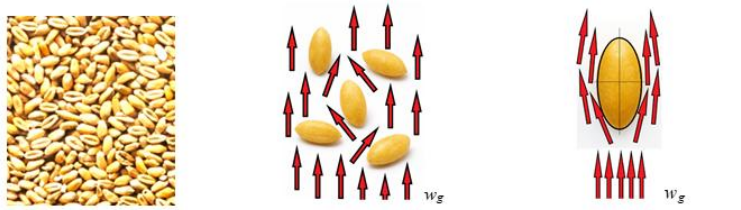
This will lead to a proportional decrease in the volumetric flow rate of the gas medium supplied by the blower, followed by the restoration of the fluidizing agent's volumetric flow rate after the gas bubble exits the initial bed. In other words, a pulsating coolant supply is realized in a self-oscillating mode, leading to the intensification of heat and mass transfer processes. This physical model for spherical particles was verified during the granulation of organo-mineral fertilizers [[17]]. Furthermore, the porosity of the granular material around the entire perimeter of the gas bubble is practically close to ε = 0.4–0.45.

In cases where solid particles have a non-spherical shape, the physical model of interaction between the fluidizing gas and the solid particles exhibits significant differences. Wheat grains, whose shape approximates an ellipsoid, were

chosen as the granular material.

Fig. 5*a*, *b* and *c* illustrate the transformation of the granular material's positions at different fluidizing agent velocities. In the gas flow, the grain orients itself with its minimal projection along the direction of flow; therefore, the main part of the resistance falls on the lateral surface, while the frontal hydrodynamic resistance is reduced due to the formation of a smaller wake.

The change in the spatial orientation of the ellipsoids upon contact with the fluidizing agent leads to a local increase in porosity by almost a factor of two, Fig. 5.



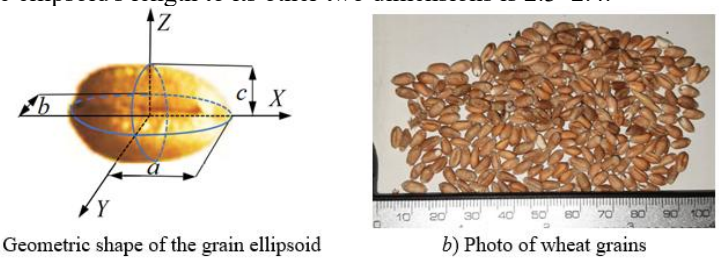
a) arrangement of wheat grains at rest (ε = 0.4)

b) location of wheat grains in the "pneumatic transport" mode ε=0.8–0.9

c) interaction of a gas flow with an individual grain

Fig.5. Identification of the geometric shape of a wheat grain

Fig. 6 shows the identification of a wheat grain with an ellipsoid having average dimensions of 6.4×2.8×2.65 mm [[18]], where the ratio of the ellipsoid's length to its other two dimensions is 2.3–2.4.



a) Geometric shape of the grain ellipsoid

b) Photo of wheat grains

Fig.6. Physical model of the interaction of a gaseous diluent with ellipsoids

To calculate the critical velocity and terminal velocity, the shape factor ψ = 0.449, calculated and used to determine the Reynolds numbers for the onset of fluidization and the terminal velocity of the ellipsoidal granular material in the apparatus:

$$Re_{mf}=\frac{\psi Ar}{1400+5.22\sqrt{\psi Ar}} \tag{4}$$

$$Re_{mf}=\frac{\psi Ar}{18+0.61\sqrt{\psi Ar}} \tag{5}$$

Where:

- Ar: The Archimedes number

$$Ar=\frac{g d_{solids}^{\ 3}\left(\rho_{solids}-\rho_{gas}\right)}{\left(\vartheta_{gas}\rho_{gas}\right)} \tag{6}$$

Where:

- d_{solids}: Equivalent diameter of solid particles, m
- ρ_{gas}: Gas density, kg/m^3
- ϑ_{gas}: Kinematic viscosity of the gas, m^2/s

Then the minimum fluidization velocity and terminal velocity for the granular material are calculated by equations (7) and (8), m/s:

$$w_{mf}=\frac{Re_{mf}\vartheta_{gas}}{d_{solids}} \tag{7}$$

$$w_t = \frac{Re_t \vartheta_{gas}}{d_{solids}} \tag{8}$$

Mass transfer during moisture evaporation from the seed surface is described as, kg/s:

$$M = \beta \Delta P_{MT} F_{MT} \tag{9}$$

Where:
- β: Mass transfer coefficient, kg/(m²sPa)
- ΔP_{MT}: Mass transfer driving force, Pa
- F_{MT}: Active interfacial area, m²

The mass transfer driving force is accepted as the difference in partial vapor pressures, Pa:

$$\Delta P_{MT} = P_{sat}^{*} - P_{bulk} \tag{10}$$

Where:
- P_{sat}^{*}: Saturated vapor pressure at the surface (at the surface temperature), Pa
- P_{bulk}: Partial vapor pressure in the bulk gas phase, Pa

The nominal pressure drop for a fixed bed, Pa:

$$\Delta P_{bed} = H_0 (1 - \varepsilon_0) \rho_{solids} g \tag{11}$$

Where:
- H_0: Initial bed height, m

The total active interfacial area of the particles in the bed can be calculated by the expression:

$$F_{MT} = \frac{6 \Delta P_{bed} S_a}{d_{solids} \rho_{solids} g} \tag{12}$$

By substituting expression (11) into equation (12) and then determining the mass transfer rate (9), we finally obtain:

$$M = \frac{\beta (P_{sat}^{*} - P_{bulk}) 6 H_0 S_a}{d_{solids}} \tag{13}$$

Given that β has a limited value, an increase in the apparatus capacity for evaporated moisture and heat can be achieved primarily by increasing H_0 provided there is intense volumetric mixing of the granular material in the apparatus.

A distinct feature of the jet-pulsating fluidization mode [[16]] for spherical solid particles is the ratio of the vertical gas spout height z_f = 80 mm to the initial bed height H_0. At H_0 = 0.32 m and Δ = 0.04 m z_f / H_0 =0.33.

At this point, the geometric shape of the bubble at the moment of detachment at the top of the gas spout has a cylindrical form, equals 1/3 of the granulator chamber width, and is determined by the equation [[16]]:

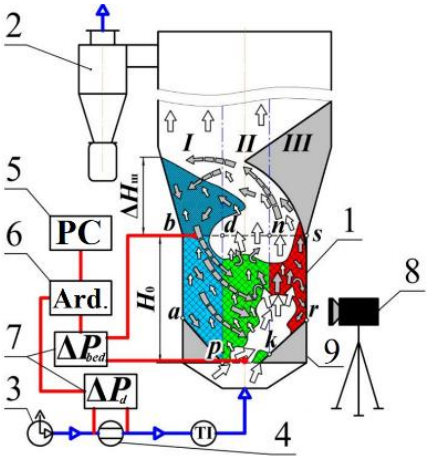
$$d_{bubble} = \frac{4\left(H_0 - z_f - \Delta\right)}{4 + \pi} \tag{14}$$

It is in this case that the maximum volumetric mixing is achieved, with more than 40% of the granular material being entrained beyond the initial bed at a frequency of J = 2.0 Hz [[16]].

4. Experimental Setup

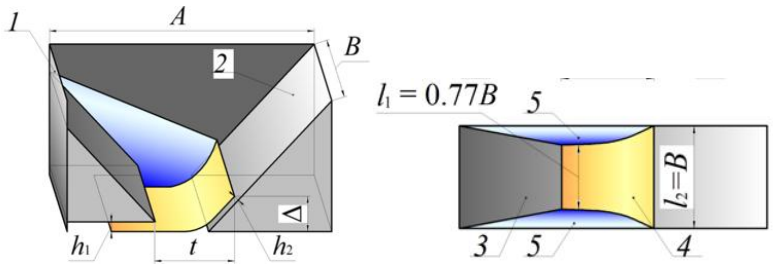
The experimental determination of the vertical spout height z_f for the ellipsoidal granular material was carried out on a pilot plant, Fig. 7.

The authors [[17], [19]] established the most rational gas distribution device (GDD) with a high level of volumetric mixing – a slit-type GDD, Fig. 8, for which the design parameters were determined, namely: height h_1 = 0.01 m and width l_1 = 0.085 m for slit 1; and height h_2 = 0.005 m and width l_2 = 0.11 m for slit 3. The hydraulic resistance coefficient of the specified GDD is ξ = 2.16 and the open area ratio of this GDD type is φ = 4.24 %.



1 – granulator chamber; 2 – cyclone; 3 – blower; 4 – diaphragm; 5 – PC; 6 – Arduino; 7 – pressure transducers; 8 – camera; 9 – slit-type gas distributor

Fig. 7. Experimental setup for investigating fluidized bed hydrodynamics



1 – granulator chamber; 2 – right grate; 3 – left grate; 4 – plate; 5 – narrowing insert.

Fig. 8. Design of a slit-type gas distribution device (GDD)

5. Materials and Methods

At the first stage of the research, the fluidization curve was determined to find the minimum fluidization velocity w_{mf} and the bed pressure drop ΔP_{bed}. Wheat grains, whose geometric shape approximates an ellipsoid with average dimensions of 6.4×2.8×2.65 mm and d_{solids} = 3.621 mmwere used as the investigated granular material. The ratio of the ellipsoid's length to its other two dimensions was 2.3–2.4. The physical and mechanical properties of the material were as follows: particle density ρ_{solids} =1270 kg/m^3, and bulk density ρ_{bulk} = 762 kg/m^3. The average porosity of the fixed bed was ε_0 = 0.4.

At the second stage of the research, the hydrodynamics of the inhomogeneous jet-pulsating fluidization were studied using high-speed video recording.

Limitations when conducting an experiment:

1. To determine the conditions ensuring the elimination of dead zones on the working surfaces of the GDD at a given initial height of the granular material bed.
2. To conduct a detailed study of the hydrodynamics under the determined conditions of the absence of dead zones on the GDD working surfaces, depending on the initial height of the granular material bed.
3. To conduct experiments at a base initial static bed height of H_0 = 0.32 m and at an increased bed height of H_0 = 0.52 m to compare the volumetric mixing of the material.
4. To perform visual recording of the gas bubble evolution with a strict time interval between frames of $\Delta\tau$ = 0.033 s for accurate analysis of the self-oscillating cycle and calculation of the entrained material volume.

6. Results and Discussion

The fluidization curve, Fig. 9., shows an increase in hydraulic resistance at the minimum fluidization velocity by a value of $\Delta\pi$=850 Pa.

This means that at the minimum fluidization velocity w_{mf} = 0.78 m/s the pressure spent on overcoming friction forces $\Delta\pi$ is almost 850 Pa, which is practically 50% of the nominal hydraulic resistance value. The second feature is a significant decrease in hydraulic resistance on the fluidization curve during the reverse path, Fig. 9. This indicates that at this static bed height, a spouted fluidization regime is realized for ellipsoidal solid particles [[20]]. Furthermore, recent experimental

and numerical studies on spouted beds confirm that optimizing gas inlet velocity and static bed height is crucial for managing pressure fluctuations and stabilizing the cross-domain hydrodynamics of the solid particles [[21]].

The photographs below, showing changes in the inhomogeneous fluidization hydrodynamics with a time interval of 0.033 s between frames, confirm the presence of only the spouted fluidization regime.

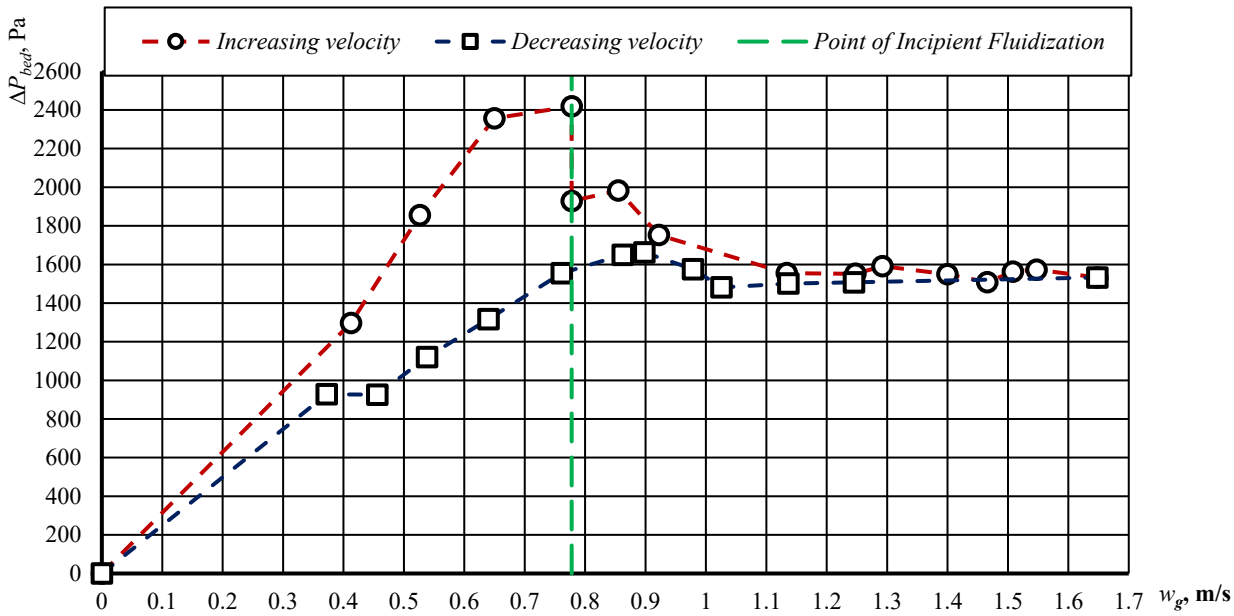


Fig. 9. The fluidization curve at H0=0.32 m (wmf = 0.78 m/s)

The experiments were conducted under conditions ensuring the elimination of dead zones on the GDD working surfaces: K_w = 2.12; w_g = 1.65 m/s; w_{slits} = 38.9 m/s.

At the first pulsation stage $0 \le \tau \le 0.132$ s, Fig. 10., a localized active zone is formed near the right side of the apparatus chamber in zone *III*. A shift of the upper part of the bed is observed; particles from the upper horizon are entrained by the flow and carried into the upper chamber, forming a "spout ejection".

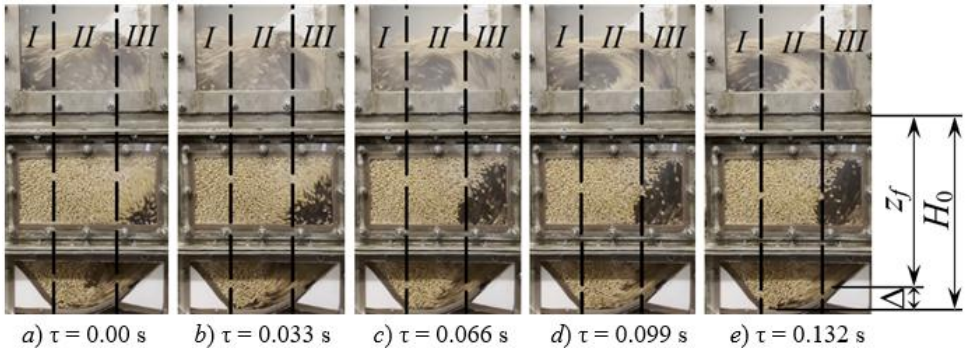


Fig. 10. Photo recording of the state of the granular material bed in the granulator chamber at the first pulsation stage $0 \le \tau \le 0.132$ s (H_0 = 0.32 s; *d*e = 3.621 mm; K_w = 2,12; $w_{g(прив)}$ = 1.65 m/s; w_{slits} = 38.9 m/s; γ = 29.67)

At the same time, the left part of the bed in zones *I* and *II* maintains a denser state: the bed boundary there is more distinct, and the bulk of the material remains at the bottom. Even at this stage, it is evident that the process has a jet-like character rather than "classical" bubbling fluidization: a large single bubble does not form; instead, there is a narrow zone of intense particle entrainment in zone *III*.

At the second pulsation stage $0.165 \le \tau \le 0.297$ s, Fig. 11, the intensity of particle entrainment in zone *III* increases and transitions into a stable local flow resembling "pneumatic transport": material from the upper part of the bed is picked up, accelerated, and ejected upwards, while a pronounced circulation forms in the lower chamber.

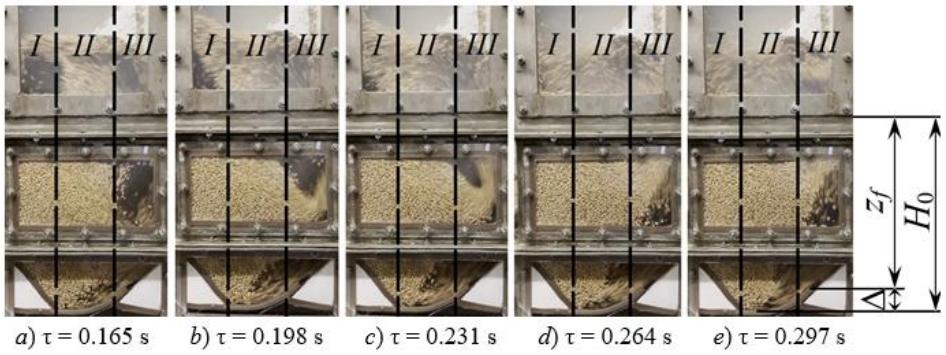


Fig.11. Photo recording of the state of the granular material layer in the granulator chamber at the second stage of pulsation $0.165 \le \tau \le 0.297$ s (H_0 = 0.32 m; d_e = 3.621 mm; K_w = 2.12; w_g = 1.65 m/s; w_{slits} = 38.9 m/s; γ = 29.67)

A characteristic feature of this stage is asymmetry: active fluidization and entrainment are observed on the right in zone *III* (the bed boundary "blurs"), while on the left in zones *I* and *II*, the bed appears denser and more stable, acting as a "reservoir" from which material is drawn into the active zone *III*.

Transverse mixing across the width remains limited: rectilinear circulation along the flow trajectory dominates, rather than volumetric mixing of the material throughout the entire initial bed volume.

The conducted experimental studies indicate that the porosity ε is unevenly distributed across the width of the apparatus.

While in zones *I* and *II* the porosity is ε = 0.4–0.5, in the spout formed in zone *III*, the porosity changes to ε = 0.5–0.9, Fig. 10, 11. This is because the granular material (wheat) orients itself with its minimal projection along the direction of particle motion, which confirms the physical model formulated above.

Throughout all stages, the formation of a single bubble is not observed at spout height z_f = 280 mm, i.e., the gas bubble diameter is, m:

$$d_{bubble}=\frac{4\left(H_0-z_f-\Delta\right)}{4+\pi}\to 0 \qquad (15)$$

The active zone was formed only on the right side, while the left part maintained increased density. In this case, an asymmetric spouting circulation mode with insufficient volumetric mixing is realized, which also confirms the necessity of increasing the initial static bed height.

The hydrodynamic results at an increased bed height of H_0 = 520 mm are presented in the form of photographs, Fig. 12, and the measured data are given in Table 1. The initial bed volume in the apparatus is $V_0 = H_0 \times A \times B = 0.52 \times 0.3 \times 0.1 = 1.56\ 10^{-2}$ m^3. The obtained experimental results and hydrodynamic parameters are consistent with previous mathematical models developed for the optimization and control of granulation processes in fluidized bed systems [[22]-[28]].

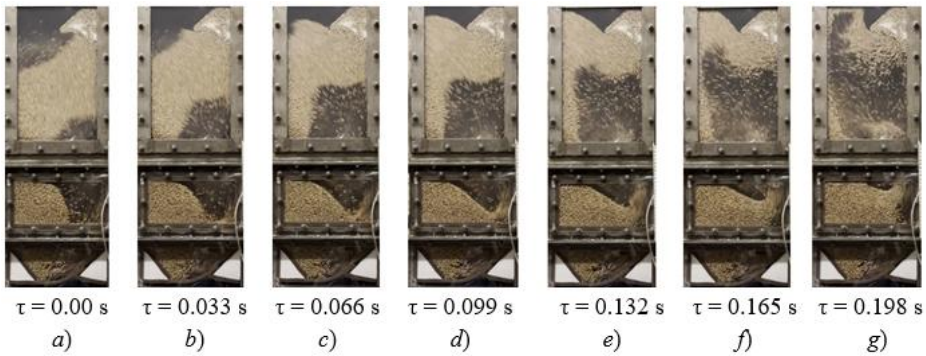


Fig. 12. Evolution of a gas bubble at H_0 = 0.52 m (d_e = 3.621 mm; K_w = 2.268; w_g = 1.55 m/s; w_{slits} = 36.48 m/s; γ = 27.86)

Table 1. Parameters of fluidized bed hydrodynamics at H_0 = 520 mm.

Position in Fig.12	***a)***	***b)***	***c)***	***d)***	***e)***	***f)***	***g)***
τ, s	0.00	0.033	0.066	0.099	0.132	0.165	0.198
d_{bubble}, m	0.145	0.170	0.185	0.190	0.220	0.240	0.250
V_{bubble}, m^3/s×10^3	1.596	2.572	3.315	5.750	5.750	7.238	8.181

A characteristic feature of increasing the bed height is the arbitrary shape of the bubble, Fig. 12, which is associated with a sharp local increase in porosity along the bubble perimeter during the induction period. Moreover, on the part of the perimeter oriented towards the vertical axis of the apparatus, the granular material rotates to minimize hydraulic resistance when interacting with the fluidizing agent and remains in motion.

The ratio of the gas bubble volume to the initial bed volume in the time interval $0 \leq \tau \leq 0.132$ s increases from 10% to 37%, Fig. 12.

The hydraulic resistance increases by the same amount, which leads to an adequate decrease in the fluidizing agent flow rate, which will be restored at the end of the cycle. Such a pulsating mode of coolant supply, together with intense volumetric mixing of the granular material in the bed, will contribute to the enhancement of transfer processes.

In addition, a significant increase in the total active interfacial contact area will make it possible to achieve the desired result with a reduced heat transfer driving force. This result was achieved at a ratio of z_f/H_0=0.538.

The conducted experimental studies have identified the conditions for the effective application of inhomogeneous fluidization to intensify transfer processes in a bed of ellipsoidal granular material.

7. Conclusion

Based on the research results presented in this article, the following main conclusions can be drawn.

1. The proposed physical model for non-spherical seed particles has been confirmed. It was established that in a gas flow, ellipsoidal wheat seeds orient themselves with their minimal projection along the flow direction, which leads to a local increase in bed porosity to $0.5 \leq \varepsilon \leq 0.9$. This spatial orientation significantly minimizes hydraulic resistance and facilitates the formation of an intense asymmetric spouting flow, where the ratio of the gas bubble volume to the initial bed volume rapidly increases to 37%.
2. Thus, the use of inhomogeneous jet-pulsating fluidization in a self-oscillating mode provides active volumetric mixing and intense circulation of the seed material, with more than 40% of the initial bed mass being pulsationally entrained into the freeboard space at a frequency of 1.5–2.0 Hz. Such a specific hydrodynamic state guarantees a significant increase in the active interfacial contact area and intensifies heat and mass transfer processes. As a result, this enables highly efficient layer-by-layer presowing treatment (drying and coating) of thermolabile particles at safe low temperatures (not exceeding 40 °C), inherently reduces the physical factors leading to seed damage and completely eliminates the formation of agglomerates, which are characteristic of traditional mechanical mixers.

All the Declarations and Statements

Author Contribution Statement

Yaroslav Kornienko – Conceptualization, Methodology, Supervision, Writing – original draft.
Serhii Haidai – Investigation, Data curation, Formal analysis, Visualization, Writing – review and editing.
Dmytro Semenenko – Investigation, Data curation, Formal analysis, Software, Validation.
Bogdan Korniyenko – Writing – review and editing, Mathematical modeling.

All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The Authors declared no conflicts of interest.

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Data Availability Statement

The data that support the findings of this study are from the corresponding author upon reasonable request.

Ethical Declarations

This study did not involve human participants or animals.

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Declaration of Generative AI in Scholarly Writing

During the preparation of the manuscript, the authors carefully reviewed the content and take full responsibility for the

accuracy and integrity of the manuscript.

Abbreviations

The following abbreviations are used in this manuscript:
GDD – Gas Distribution Device

APPENDIX:

Not applicable.

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