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INCREASING OF THE HEAT AND MASS TRANSFER PROCESSES EFFICIENCY WITH THE APPLICATION OF NON-UNIFORM FLUIDIZATION

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ABSTRACT

The use of non-uniform jet-pulsating mode of fluidization allows increasing the intensity of diffusion-controlled processes of mass isothermal crystallization in granulation of liquid heterogeneous systems due to the intensive volumetric mixing of granular material by pulsating removal beyond the initial layer up to 40% of its mass with a frequency of 1.6...1.8 Hz. Efficiency of application of the non-uniform jet-pulsating mode of fluidization is confirmed by the granulation of multicomponent liquid heterogeneous systems with obtaining humic-potassium-nitrogen-calcium-sulfur-containing fertilizer with micro-impurities of magnesium and phosphorus with chemical composition [Hum.]:[K]:[N]:[Ca]:[S]:[Mg]:[P]=[1.5]:[21.5]:[9.1]:[13.8]:[4.6]:[3.2]:[1.8] with a layered structure, spherical shape with an equivalent diameter in the range $d_{average}$=2.2...3.6 mm and a strength P greater than 12 N per granule. In this case the granulation coefficient ψ is more than 85%, and the average specific load of bed by moisture is at least 1.5 times higher than this index in the case of homogeneous fluidization.

Keywords: non-uniform fluidization, jet-pulsating mode of fluidization, bed temperature, kinetics of granulation process, coefficient of granulation, specific load of the bed surface by moisture.

INTRODUCTION

It is possible to obtain granulated product with different structures when granulating liquid systems in a fluidized bed [1, 2].

The obvious advantage of this method is the significant increase in the heat utilization factor and the implementation of the process of mass crystallization on the surface of the granules, in which the microcrystals with a size of $1...10\cdot10^{-6}$ m is deposited colloidal particles of organic matter and to form complexes with suspended particles of impurities in the size of $5...10\cdot10^{-6}$ m.

Such results are reported in publications [3-29] in obtaining humic-mineral fertilizers with different nutrient, deoxidizing and humic substances ratio [30-33].

An integral indicator of the quality of kinetics is the coefficient of granulation, which shows the percentage of fixed on the surface of granules solids from substances entering the apparatus with the liquid phase.

The peculiarity of granulation of new generation humic fertilizers is the need for even distribution throughout the volume of granules of humic substances, the content of which does not exceed 2%.

Therefore, the most appropriate to achieve this goal is a layered granulation mechanism, described in detail in the publications [3-46].

In this case, a bubbling or bubble-fountaining mode of fluidization was used [4-30], and the specific bed load by the moisture was af a_f=0.2...0.33 $kg_{moisture}/(h\cdot m^2)$.

In order to intensify the heat transfer processes, the authors [45, 46] proposed a non-uniform fluidization with the use of an external mechanical device mounted directly on the supply line of the coolant for the treatment of heat-resistant materials that are not melted on the fracturing surfaces [45, 46].

In the case of granulation of liquid thermolabile systems based on ammonium sulfate, the use of this method of implementation of non-uniform fluidization is impossible.

In works [35-58] the conditions for the implementation of non-uniform mode of fluidization in auto-oscillating mode without the use of external mechanical devices for granulation of thermolabile substances are defined, and the methods for evaluating the quality of the hydrodynamic mode of non-uniform fluidization are formulated.

MATERIALS AND METHODS

For carrying out the studies was used an experimental unit consisting of a granulator in the form of a parallelepiped with sizes AxBxH=0.3x0.11x1.2 m from stainless steel H18N10T, equipped with the slit-type gas-distributing device with a coefficient of live intersection of φ=4.9 in the lower part and the guiding insert in the upper part [41].

The height of fixed bed in the apparatus was H_0=0.32 m. As initial granulation centers used spherical granules of ammonium sulfate with impurities of humic substances with equivalent diameter d_e=2.5 mm.

The liquid homogeneous and heterogeneous phase formed on the basis of aqueous solutions of ammonium sulfate was dispersed inside the fluidized bed using a mechanical dispersant in the form of a perforated

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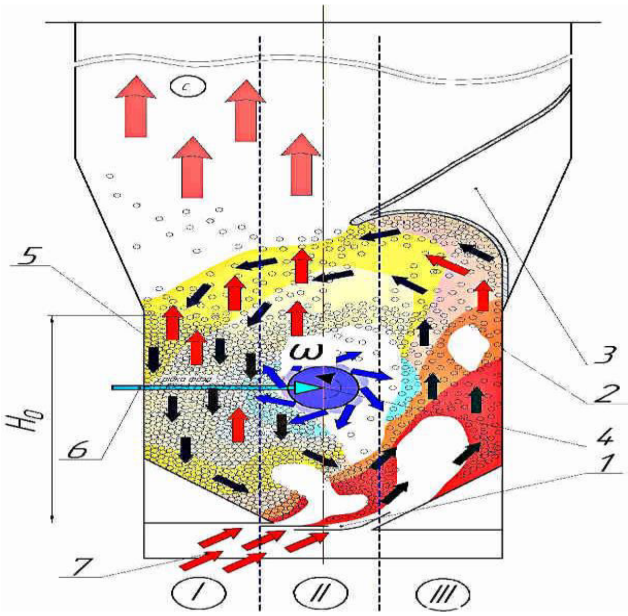
cut cone with diameters d_1=40 mm, d_2=80 mm and height l=50mm with the horizontal axis of rotation. Frequency of rotation of the mechanical dispersant varied from 50 to 70 Hz. The mass of the bed during operation was maintained constant by unloading the granular product.

The pressure drop in the fluidized bed was measured with a water differential manometer and the temperature was measured by a computer-information complex with an accuracy of ±0.5 ºC.

RESULTS AND DISCUSSIONS

The organization of the process with non-uniform jet-pulsating fluidization in an auto-oscillating mode is shown on Figure 1 [35].

Past studies [35-39] shown that in the operating mode of jet-pulsating fluidization in the apparatus, Figure-1, it is possible to distinguish 3 zones by hydrodynamic features.



1 - GDD; 2 - chamber of granulator; 3 - guiding insert; 4 - rotating dispersant; 5 - bed of granular material; 6 - supply of liquid phase; 7 - supply of coolant.

Figure-1. Model of granulation with the use of non-uniform fluidization [35].

Zone *I* - zone of downward movement of the granular material to which, due to the asymmetric supply of coolant (fluidizing agent), the granular material is displaced due to inertial removal from zone *II* and *III* in the upper part of zone *I*. The bed porosity in this zone is mostly constant $\varepsilon_I=\varepsilon_0$=0.4 maximum height increases to (1.7...2)H_0 and the movement of the gas coolant in this zone occurs only in the filtration mode, the dynamics of the variation of the porosity is shown on Figure-1.

Zone *II* - boundary zone in which 3D mixing of granular material occurs due to the movement of gas bubbles and displacement of a large cluster of granular material mainly from zone *I* in their place. The porosity in this zone changes cyclically ε_{II}=0.45→0.68→0.45, Figure-1. In the middle of this zone at a height of 0.68H_0 from the gas distributing device (GDD) surface is a mechanical cone type dispersant.

Zone *III* - the zone in which the active flow of gas jets exiting the slits of the GDD occurs and leads to the formation of a gas bubble that almost completely fills the intersection of zone *III* at the moment of movement in the vertical direction. This leads to the inertial removal of a large amount of granular material in the overlay, when interacting with the guiding insert 4, moves to zone *I*. Thus, an active upward movement of the granular material is formed in zone *III*, which is characterized by a cyclic change in the porosity ε_{III}=0.45...0.75. The height of the vertical torch of the gas jet is 3 times smaller than the height of the initial fixed bed H_0 [35].

The peculiarity of the process of non-uniform jet-pulsating mode of fluidization in auto-oscillating mode is the presence of three stages in one cycle [35, 45], Figure-2.

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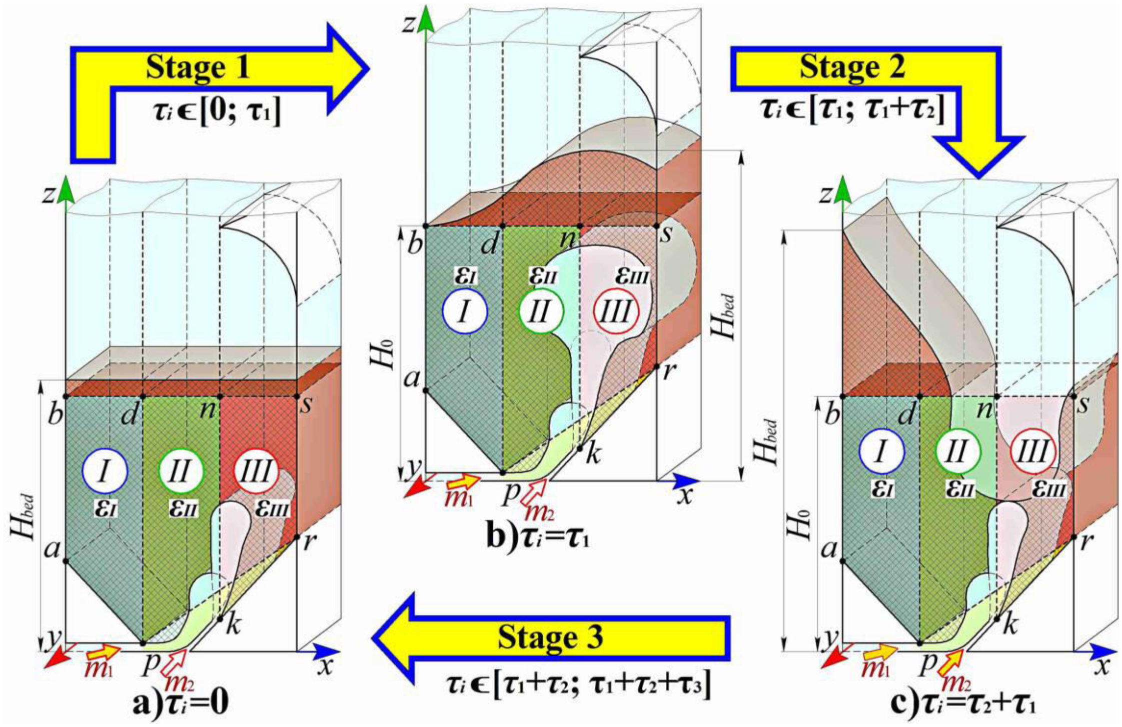


Figure-2. Physical model of non-uniform jet-pulsating fluidization in auto-oscillating mode.

Stage 1 – τ_1 – the time of gas bubble formation at the boundary of the zone *II* and *III*;

Stage 2 – τ_2 – movement of the gas bubble and removal of material into the overlay;

Stage 3 – τ_3 – movement of granular material into formed voids in zones *II* and *III*.

It means that the total time of the cycle is $\tau_c=\tau_1+\tau_2+\tau_3$, Figure-2.

Porosity in zones was determined in the volume of the initial bed, Figure-2, and the dynamics of porosity changes in these zones are shown on Figure -3.

As a result of generalizing results of the study [34-38] is obtained correlation dependence for calculating the average porosity in the apparatus during the jet-pulsating mode of fluidization while maintaining the index of dynamic quality $i_q \to 1$ [38].

It is proposed to determine the velocity of solids as $W_s=d\varepsilon/d\tau$.

Therefore, the dynamics of the change of the velocity of solids by zones is shown on Figure-4 and the relative velocities of the coolant, taking into account the direction of the velocity vector of solids are shown on Figure-5.

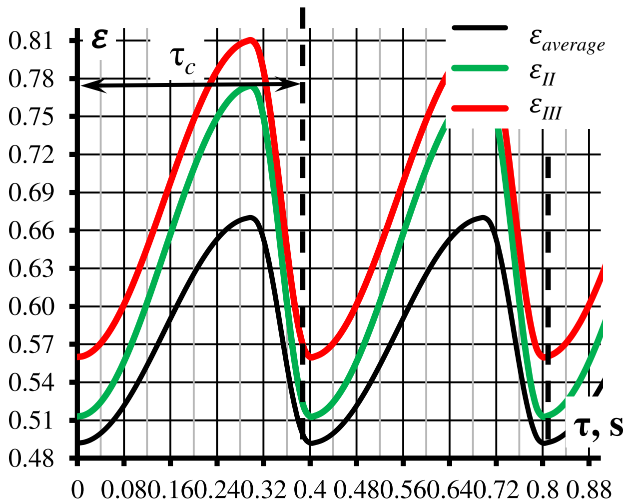


Figure-3. Dynamics of the porosity changes in zones (*Conditions:* $d_{average}$=2.5 mm; $w_{g(average)}$=1.6 m/s; K_w=2.05).

Estimated average values of gas velocity w_g – $d\varepsilon/d\tau$ shown on Figure-4 shows that except $1/3\tau_c$ at the end 0.25 Hz is three times higher than the value of the average gas velocity W_r=1.6 m/s, and when moving material from the space beyond the bed to the initial state is 4.6 times higher.

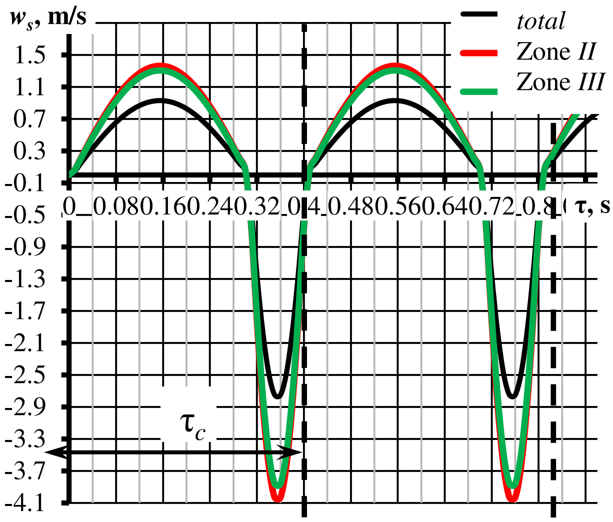


Figure-4. Dynamics of change of velocity of solid particles in a layer of granular material by zones (*Conditions:* $d_{average}$=2.5 mm; $w_{g(average)}$=1.6 m/s; K_w=2.05).

This leads to a decrease in the thickness of the diffusion sublayer formed on the surface of the granules, which promotes the intensification of mass transfer through this layer.

The dispersant rotates in the direction of the vertical circulation of the granular material in the apparatus, and the cyclic dynamics of the variation of the porosity in zones *II* and *III* promotes intensive three-dimensional mixing of the material.

Determination of the temperature field in the dispersant zone in the main technological zones will allow determining the intensity of heat transfer processes.

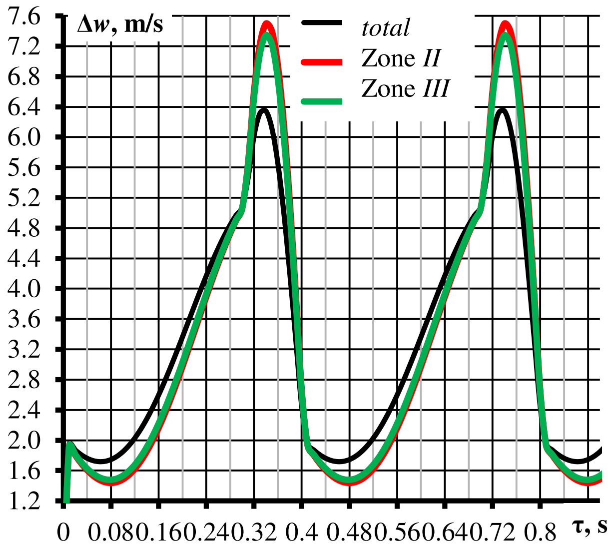
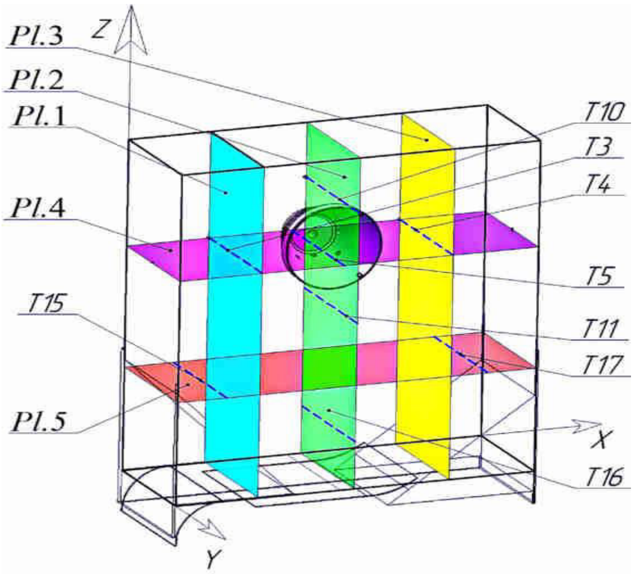


Figure-5. Estimated relative values of the velocity of the coolant with the velocity vector of the solid phase (*Conditions:* $d_{average}$=2.5mm; $w_{g(average)}$=1.6m/s; K_w=2.05).

To measure the temperature in the working chamber of the granulator are arranged conditional planes that pass in the middle of the hydrodynamic zones *I*, *II*, *III* in which the tracks of thermocouples and a plane 4 that passes horizontally through the axis of rotation of the dispersant, Figure-6.



Pl.1 (x = 50 mm; y = 0...110 mm; z = 0...500 mm)
Pl.2 (x = 150 mm; y = 0...110 mm; z = 0...500 mm)
Pl.3 (x = 200 mm; y = 0...110 mm; z = 0...500 mm)
Pl.4 (x = 0...300 mm; y = 0...110 mm; z = 220 mm)

Figure-6. Arrangement of tracks of thermocouples in the chamber of the granulator in conventional planes.

The mathematical model of heat transfer is based on the authors' equation [48] that is supplemented by the energy consumption for heating the liquid phase on the surface of granules in the form of a film, and the cost of heating and evaporation of the solvent taking into account the intensification of diffusion-controlled processes. Then the heat balance equation for the gas coolant is written in the form:

$$\varepsilon_g \cdot \rho_g \cdot C \cdot \frac{\partial T_g}{\partial t} + W_g \cdot \varepsilon_g \cdot \rho_g \cdot \frac{\partial T_g}{\partial x} =$$
$$= \varepsilon_g \cdot a \cdot \frac{\partial^2 T_g}{\partial y^2} - \alpha \cdot F \cdot (T_g - T_s) + G_{liq.} \cdot (1 - x_{liq.}) \cdot (r + C_w \cdot T_s)$$

For solid granules:

$$(1-\varepsilon_g) \cdot \rho_s \cdot C_s \cdot \frac{\partial T_s}{\partial t} - W_s \cdot (1-\varepsilon_g) \cdot \rho_s \cdot \frac{\partial T_s}{\partial x} = \alpha \cdot F \cdot (T_g - T_s) -$$
$$- G_{liq.} \cdot (1 - x_{liq.}) \cdot (r + C_w \cdot T_{bed}) + G_{liq.} \cdot x_{liq.} \cdot q$$

where ε_g – bed porosity (the share of gas)
ρ_g – gas density, kg/m^3;
ρ_s – density of solids, kg/m^3;
W_g - gas velocity, m/s;
C_g – gas heat capacity, kJ/(kg·K);
λ_g – thermal conductivity of gas, W/(kg·K);
F – the specific surface of granules in bed with given height, m^2/m^3;
F=6(1-ε_0)/d_e; d_e=1/Σ(x_i/d_i)
$d_{average}$ – average diameter of solids, mm;

x_i – mass fraction of solid particles, %;
d_i – average size of fraction, mm;
$G_{liq.}$ – specific mass load of the bed of granular material, kg/(s·m^3);
$X_{liq.}$ – the concentration of solids in the solution supplied to the granulator, %(mass)
T_g, T_s – temperature of the coolant at the inlet to granulator and the temperature of solids bed, °C;
C_w – water heat capacity, kJ/(kg·K);
$C_{liq.}$ – heat capacity of the solution supplied to granulator, kJ/(kg·K);
q – effective crystallization heat, kJ/kg;
r – specific heat of vaporization, kJ/kg;
W_s - solids velocity, m/s;
α – coefficient of heat transfer from gas to surface of solids (granules), W/(m^{2}K);
a – coefficient of thermal conductivity, m^2/s.

Substantiation of bed temperature

To solve the equation, it is necessary to justify the temperature in the fluidized bed. According to the results of previous studies, the temperature in the fluidized bed cannot exceed 98 °C during dehydration and granulation of solutions of ammonium sulfate, since this leads to significant extraction of ammonia and increasing of acidity of granules. On the other hand, reducing the temperature of granules to 80-85 °C is accompanied by a significant deterioration of the kinetics of granulation, which is resulting in the decreasing of granulation coefficient to 75...80%. Therefore, is accepted that half of moisture from the film of liquid formed on the surface of granules is evaporated due to the heat coming from the heated granule. The rest of required heat is coming convectively from the heated coolant.

Therefore, given that the maximum amount of ammonium sulfate solution is:

$$M_{solution} = 0{,}1 \cdot M_{granule}, \tag{1}$$

then the amount of liquid in solution on the surface of the granule is:

$$M_{H_2O} = 0{,}1 \cdot M_{gr} \cdot (1 - x_{liq.}) \tag{2}$$

where x_p– mass fraction of solids in solution.

Whence the amount of solvent that must be evaporated from the film of liquid upon application to the granule will be:

$$M`_{H_2O} = M`_{H_2O}/2, \tag{3}$$

Taking into account the consumption of heat, it is possible to calculate only the required amount of convective heat input:

$$Q_{c.h.i.} = M`_{H_2O} \cdot r, \tag{4}$$

where r=2448 kJ/kg – specific heat of vaporization at t=20°C.

The required amount of heat that is convectively supplied to granule:

$$Q_{gr} = M_{gr} C_{gr} \cdot (T_s - T_M), \tag{5}$$

where C_{gr} – heat capacity of ammonium sulfate granules. Thus from equations (2) and (5) follows, that:

$$M`_{H_2O} \cdot r = M_{gr} C_{gr} \cdot (T_s - T_M) \tag{6}$$

hence:

$$T_s = \frac{0{,}1 \cdot (1 - x_{liq.}) \cdot r}{2 \cdot C_{gr}} + T_M \tag{7}$$

The average velocity of gas coolant is calculated by a known method [49].

The coefficient of heat transfer from gas to wet granules in fluidized bed was calculated by the method [50], it's acquired value α=140–250 W/(m^2°C) depending on the distance from GDD.

Porosity is determined by the the method [46].

System (1) was solved by the Euler method for systems of second order differential equations using iterative refinement of the solution of equations. The coefficients were accordingly adjusted using numerical integration methods for better convergence. To solve system (1) was created a program using Borland Delphi environment using the Math module. The results of calculation of coolant temperature and temperature of solid granules are respectively shown on Figures 7 and 8.

The calculated data show the convergence with the experimental data. The correlation coefficients are R=0.943 and δ=0.956 that confirms the adequacy of the model of the dynamics of the temperature field change during granulation from heterogeneous liquid systems in the fluidized bed with the use of conical dispersant and allows to determine temperature for implementation of stable kinetics of the process.

Organic-mineral fertilizers with $d_{average}$=1.85 mm were used as the initial granulation centers. During the experiments, the initial height of the fixed bed was kept constant by unloading the granular product and was H_0=0.32 m, which corresponds to the mass of bed M_{bed}=7.83 kg and hydrostatic pressure $\Delta P_{hydrost(0)}$=2389 Pa. The liquid heterogeneous solution was dispersed inside the bed using a mechanical dispersant. By order of the firm «*EcoPlant*» and private enterprise «AgroZar» the solution contained such dry components as sunflower ash (S.A.) - 52.5%(mass), ammonium sulfate (A.S.) - 43 %(mass), bentonite (B.) - 3 %(mass), humic substances (H.S.) - 1,5 %(mass). The water content of the solutions in experiments 1 and 2 was 60 %(mass), in experiments 3 and 4 - 50 %(mass).

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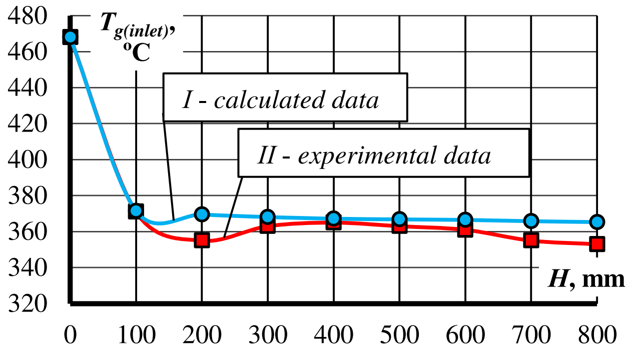

Figure-7. Dynamics of temperature change of coolant on the height of the apparatus.

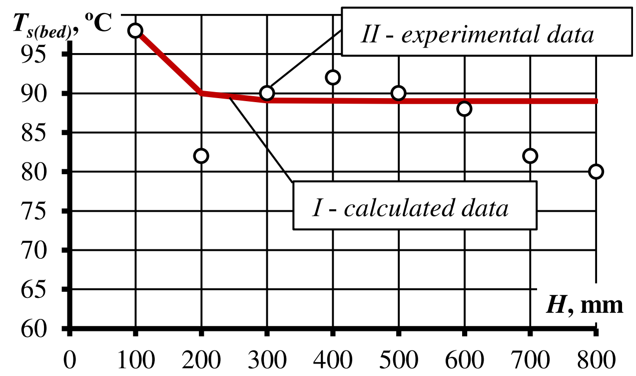

Figure-8. Dynamics of temperature change of coolant on the height of the apparatus.

The stability of the granulation kinetics is confirmed by the stable dynamics of growth of the equivalent (average) particle diameter in the bed, Figure 9, with the successive transition of granules from the smaller to larger fractions, Figure 10, which confirms the layered mechanism of granulation without the formation of agglomerates. The bed temperature was maintained within the specified limits T_{bed}=95±2 °C, Figure-11.

In this case, the average specific load of bed by moisture a_f in 1,5 ... 1,94 times higher than the indicators when applying the bubbling mode of fluidization, Figure 12, with the achievement of the granulation coefficient ψ=80...98%, Figure 13, that confirms stability of the process kinetics.

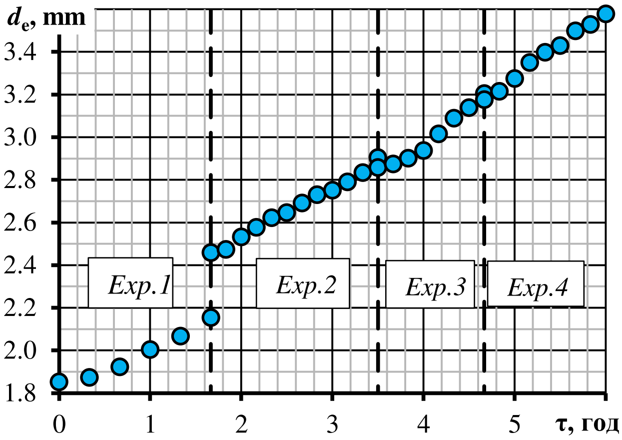

Figure-9. Experimental dynamics of change $d_{average}=f(\tau)$.

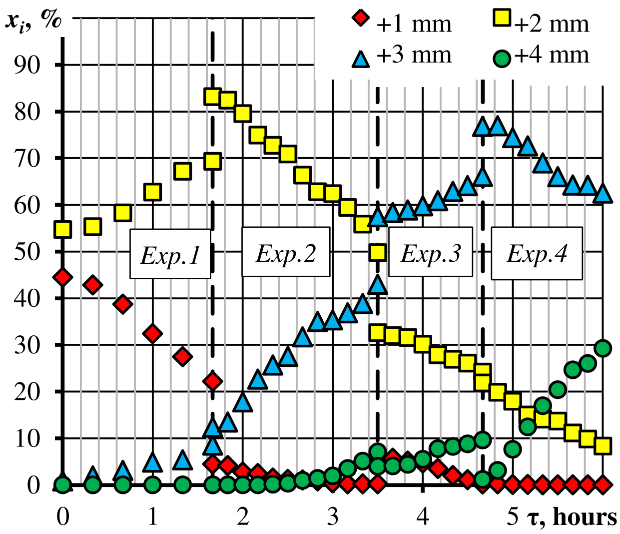

Figure-10. Experimental dynamics of change $x_i = f(\tau)$.

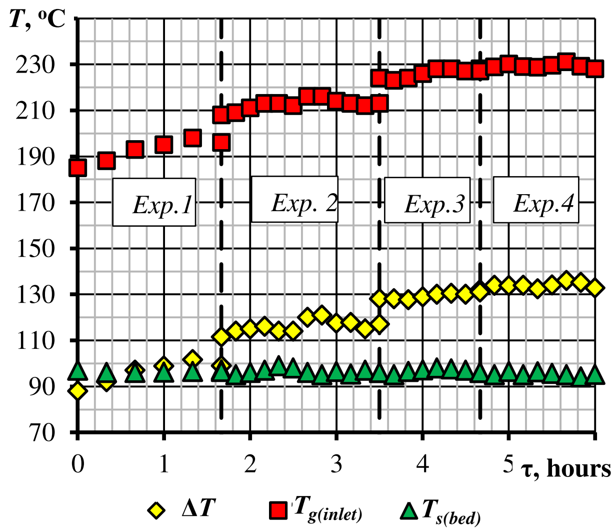

Figure-11. Experimental dynamics of change $T_i = f(\tau)$.

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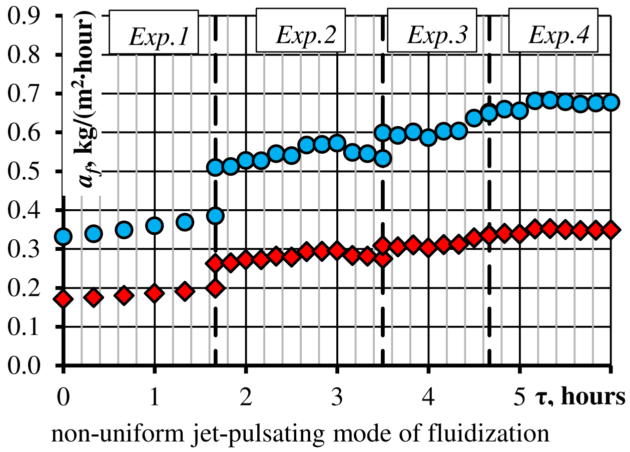


Figure-12. Experimental dynamics of change $a_f=f(\tau)$.

The experiments were carried out at values of fluidization coefficient K_w in terms of the normal conditions of realization of qualitative non-uniform fluidization in the range $K_{w(\max)}\leq K_w\leq K_{w(\min)}$, Figure-14. Is established that even at calculated values of the dynamic quality index of hydrodynamics $0.8\leq i_{quality}\leq 0.98$, Figure-15, there is no melting of solid granules on the working surfaces of gass distributing device (GDD) after a number of experiments.

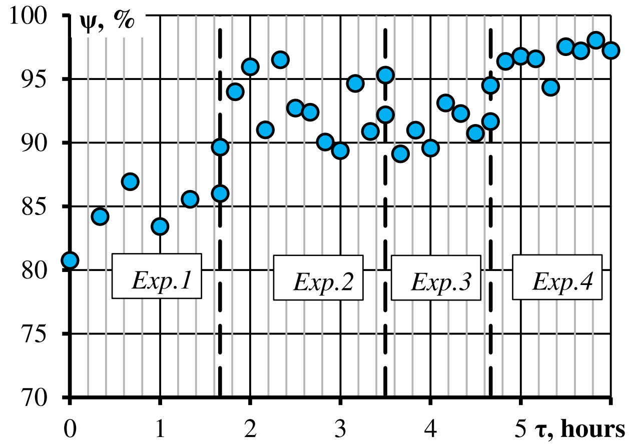


Figure-13. Experimental dynamics of change $\psi=f(\tau)$.

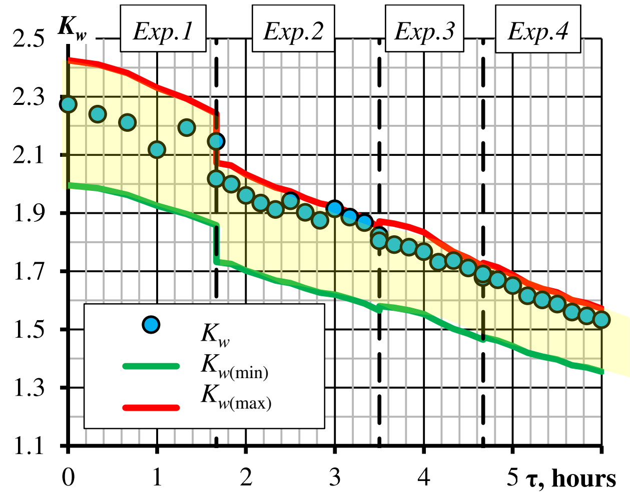


Figure-14. Experimental dynamics of change $K_w=f(\tau)$.

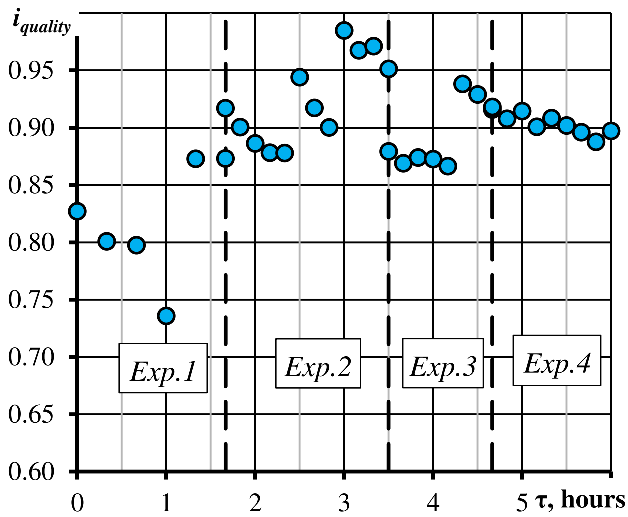
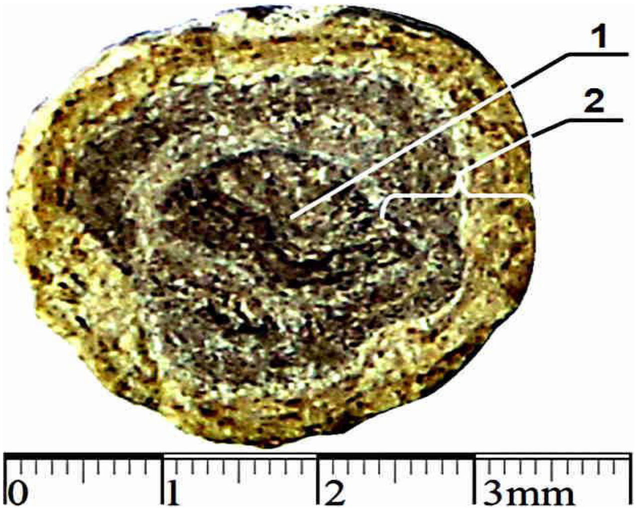


Figure-15. Experimental dynamics of change $i_{quality}=f(\tau)$.

Granular product of humic-potassium-nitrogen-calcium-sulfur-containing fertilizer with micro-impurities of magnesium and phosphorus, Figure-16, with chemical composition [Hum.]:[K]:[N]:[Ca]:[S]:[Mg]:[P] = [1.5]:[21.5]:[9.1]:[13.8]:[4.6]:[3.2]:[1.8] is with spherical shape with a layered structure, which achieves a uniform distribution of components throughout the volume of the granule with $2.0\leq d_{average}\leq 4.0$ mm. Strength of the granules for fraction +2.0...+4.0 mm is 12...16 Newton per granule, which is 1.2...1.6 times higher than the minimum permissible normative index. No analogues of this kind of fertilizers were found in the world.



1 – granulation center; 2 – composite micro layers
Figure-16. – Granule in cross-section ($d_{average}$=3.4 mm).

CONCLUSIONS

The use of non-uniform jet-pulsating mode of fluidization in the process of dehydration and granulation of multicomponent liquid systems provides intensification of heat-mass transfer processes in the diffusion sublayer located directly near the surface of the wetted granule.
Asymmetric jet injection of a coolant heated to temperature of 240°C contributes conservation of the driving force in mass transfer at height of more than 50% of the initial bed. This eliminates the risk of formation of stagnant zones on the working surfaces of gas distribution device. This allowed to increase the average specific load of bed by moisture a_f in 1.5, compared to homogeneous fluidization, and provided a granulation factor ψ≥85%.

The obtained granular product of the composition [Hum.]:[K]:[N]:[Ca]:[S]:[Mg]:[P]= =[1.5]:[21.5]:[9.1]:[13.8]:[4.6]:[3.2]:[1.8] has a layered structure, a spherical shape with an equivalent diameter in the range $d_{average}$=2.2...3.6 mm and a strength P≥12 N per granule.

The mathematical model of heat-mass transfer with the application of non-uniform jet-pulsating mode of fluidization adequately describes the experimental data for the temperature of coolant and the temperature of granules with similarities δ=5.7% and δ=4.4% respectively.

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