RESEARCH, DESIGN, CALCULATIONS, AND OPERATING EXPERIENCE

PROCESSES AND EQUIPMENT FOR CHEMICAL AND OIL-GAS PRODUCTION

INTERNAL RECYCLED PARTICLES CIRCULATION IN VORTEX GRANULATOR

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A theoretical model that describes the internal recycled particles separation process in suspended-layer vortex granulators (SLVG) with a height-variable cross-sectional area is presented. Relationships are derived to determine the recycled particles circulation time in SLVG with a specified configuration. The calculated results are confirmed by experimental studies on an SLVG prototype. The results of the analytical solution of the equations of the mathematical model can be used to design SLVG with an internal recycled particles circulation, which can be organized in various ways, depending on the need for simple recirculation or the presence of additional recycled particles thermal treatment stage during recirculation.

Keywords: *suspended-layer vortex granulator, hydrodynamics, internal circulation, recycled particles.*

It is well known that swirling of flows is one of the most efficient passive methods of intensifying heat and mass transfer processes [1]. This method was used to develop new designs of suspended-layer vortex granulators (SLVG) (Fig. 1). A distinctive feature of the unique designs of the SLVG is the possibility of realization of the process of internal circulation of recycled particles (fine granules of noncommercial fraction, which are formed after crystallization of drops of melt of fine particles). The proposed design solutions are based on inventor's developments [2–4].

Several works, where hydrodynamics of flow motion [5, 6], granule classification and separation processes [7], ecological aspects of development of a block of production waste utilization modules [8–10], and hydro- and thermodynamic conditions for producing granules with a porous structure [11] are described, were dedicated to a theoretical description and experimental study of individual aspects of granulation in vortex apparatuses. In spite of a fairly comprehensive description of the hydrodynamic granule formation conditions in vortex granulators, the procedure of calculation only for the working part of the granulator (internal casing) has been developed so far. Lack of a mathematical apparatus for calculating the internal recycled particles circulation process is an impediment to the determination of the optimal vortex granulator operation conditions in a wide range of productive capacities.

This work is aimed at providing a mathematical description of the internal recycled particles circulation process in an SLVG. Various ways of organizing recycled particles movement in the interannular space of the vortex granulator are proposed. A fine fraction of granules up to 0.2 mm in size was used as the recycled particles.
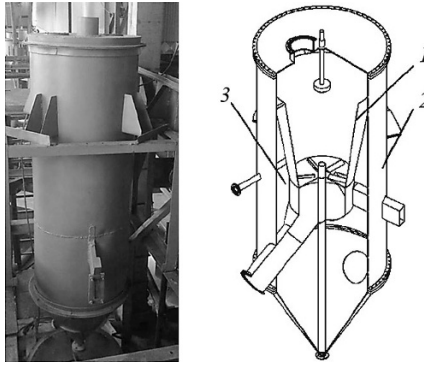
Fig. 1. Vortex granulator with internal recycled particles circulation:
1) internal (working) cone; *2*) external casing; *3*) interannular space.

Cases where the recycled particles fall into still air and into an ascending air stream and also move with multistage contact with a heat carrier were studied in this work. SLVG calculation schemes for different recycled particles circulation conditions are illustrated in Fig. 2.

The design parameters of the internal casing of the SLVG ($R_1^{\mathrm{up}}, R_1^{\mathrm{low}}, \gamma_1, H_1$) are chosen on the basis of classification of polydisperse granules of a specified fractional composition into a required number of fractions in conformity with the mathematical model [7]. The design parameters of the main casing (shape, $R_2^{\mathrm{up}}, R_2^{\mathrm{low}}, \gamma_2, \gamma_3, H_2, H_3, d_{\mathrm{c.p}}, H_{\mathrm{c.p}}$) are determined by the results of optimization calculation based on the proposed mathematical model.

Free recycled particles motion in still air. In keeping with Fig. 2, let us divide individual segments with different laws of motion in the recycled particles motion path:

section I – motion of a body thrown at an angle to the horizon with an initial velocity (segment *AO*);

section II – free fall of a body or motion of a body thrown at an angle to the horizon with an initial velocity (segment *OB*);

section III – motion of a body thrown at an angle to the horizon with an initial velocity (segment *BC*);

section IV – motion of a body in pneumatic transport mode (segment *CD*).

Then, the recycled particles circulation time

$$\tau_{\mathrm{i.s}} = \tau_{\mathrm{I}} + \tau_{\mathrm{II}} + \tau_{\mathrm{III}} + \tau_{\mathrm{IV}}. \tag{1}$$

Let us determine the geometric parameters of the recycled particles motion and their residence time in each section. We shall use classical equations of motion of a body for the calculation [12, 13].

Section I. The maximum recycled particles lift height (point *A′*)

$$h = W_0 \sin^2 \alpha / (2g), \tag{2}$$

where W_0 is the initial velocity of flight of a particle from the internal cone, m/sec; $\alpha = 90 - \gamma_1$ is the particle flight angle to the horizon, deg; and g is the free fall acceleration, m/sec^2.

Considering that in the top part of the cone the ascending component of the gas stream velocity exerts the primary influence on the recycled particles (under conditions of transfer of up to 95% of the angular momentum to the recycled particles by the gas stream), we shall assume that the initial recycled particle flight velocity W_0 is equal to the total velocity of the components of the gas stream and is parallel to the generatrix of the internal cone. The total velocity of the gas stream is determined from the data in [7].

The h value determined by Eq. (2) is the minimum height of the separation space of the SLVG, i.e., $h = H^{\mathrm{sep}}$ (Fig. 2).

The maximum recycled particles flight radius at the level of the top section of the internal cone (point *O*)

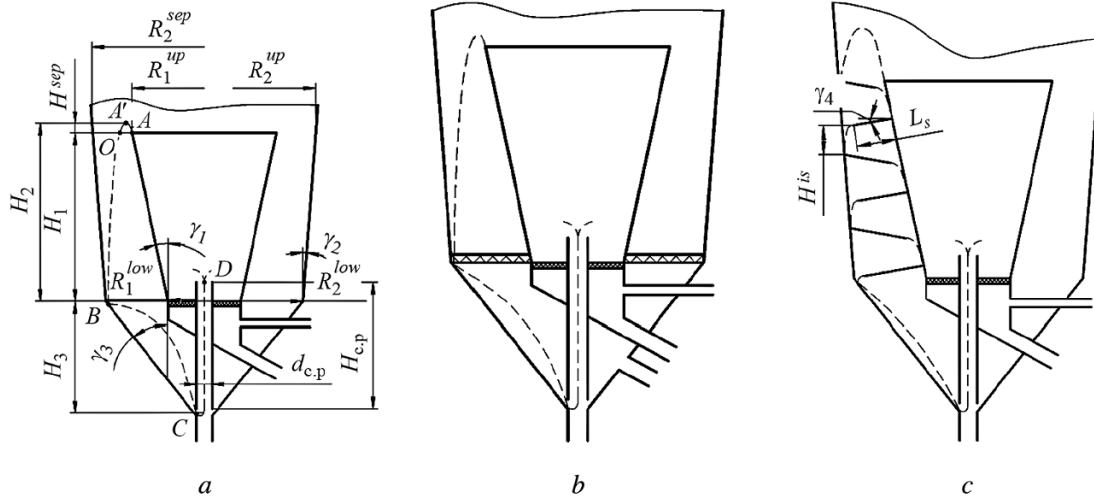$$R_{\max} = R_1^{\mathrm{up}} + L_1, \tag{3}$$

Fig. 2. SLVG calculation scheme: *a*) with fall of recycled particles into still air; *b*) with fall of recycled particles into ascending air stream; *c*) with recycled particles movement with multistage contact with heat carrier.

where L_1 is the maximum recycled particle flight distance relative to R_1^{up} at the point O, m,

$$L_1 = W_0^2 \sin 2\alpha / g. \qquad (4)$$

The recycled particle lift time

$$\tau_l = W_0 \sin \alpha / (2g). \qquad (5)$$

The full recycled particle flight time

$$\tau_I = 2\tau_l. \qquad (6)$$

The radius of the top section of the external casing is taken equal to

$$R_2^{up} = R_{max} + (0.2...0.3). \qquad (7)$$

Section II. Let us consider two variants of recycled particles motion: 1) rectilinear path (at initial expansion angle of the internal cone $2\gamma_1 \le 18°$ and the initial flight velocity $W_0 \le 1.5$ m/sec) and 2) parabolic path.

Calculations by the referred mathematical model showed that the time of granule fall into the interannular space along rectilinear and parabolic paths is the same, but in this case not only the time of motion, but also the distance of flight of the recycled particles is an important parameter. Depending on the initial recycled particle flight velocity, the degree of "parabolicity" of the motion path may vary. The phenomenon of transition of recycled particles motion from the parabolic to the rectilinear path at low velocity of flight from the internal cone and at small cone expansion angle is confirmed by calculation (Fig. 3) and experimental studies.

Variant 1: recycled particles motion from point O to point B is described as uniformly accelerated rectilinear at initial velocity $W_1 = W_0$. In this case, the final particles velocity at the point B

$$W_2 = W_1 + \sqrt{2gH_1}. \qquad (8)$$

The recycled particles flight time $\tau_{II} = f(H_1, W_1)$ is determined by solving the equation derived from the equation of uniformly accelerated rectilinear motion,

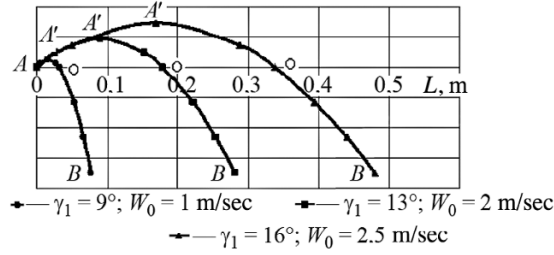$$W_1\tau_{II} + g\tau_{II}^2 / 2 - H_1 = 0. \qquad (9)$$

Fig. 3. Results of calculations of granule motion path under different initial flight conditions.
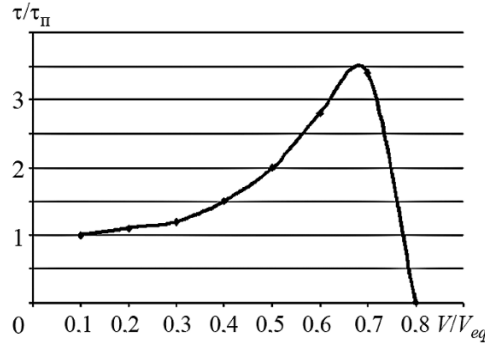

Fig. 4. Recycled particles residence time in interannular space versus gas stream velocity.

The radius of the bottom section of the external casing (m) is considered structurally equal to

$$R_2^{low} = R_{max} + (0.1...0.2). \tag{10}$$

Thus, for this case, the preferred shapes of the external casing is cylindrical ($R_2^{up} = R_2^{low}$) or conical (diverging) with a small cone expansion angle $2\gamma_2$.

The minimum height of the external casing

$$H_2 = H_1 + H^{sep}. \tag{11}$$

The minimum radius of the separation space of the external casing

$$R_2^{sep} = R_2^{up} + H^{sep}\tan\gamma_2. \tag{12}$$

Variant 2: recycled particles motion from point *O* to point *B* is considered a continuation of parabolic motion of the recycled particles thrown at an angle to the horizon.

To determine the time of recycled particles flight in the vertical direction to a height H_1, we shall write the classical equation of motion of a body thrown at an angle to the horizon with a velocity $W_1 = W_0$, assuming that the vertical coordinate of the motion will decrease and the particles flight angle to the horizon $\alpha = 90 + \gamma_1$ will be

$$-H_1 = W_1 \sin\alpha\,\tau_{II} - g\tau_{II}^2 / 2, \tag{13}$$

whence we can determine the sought quantity τ_{II}.

Further motion of the recycled particles over the flight time τ_{II} in the horizontal direction can be determined by solving the equation

$$L_2 = -W_1 \cos\alpha \tau_{II}. \tag{14}$$

The maximum motion of the recycled particles in the horizontal direction

$$L_3 = L_1 + L_2. \tag{15}$$

Then, the radius of the bottom section of the external casing is determined by Eqs. (3) and (10), substituting L_3 for L_1.

Thus, in this case, the conical (converging) shape is preferable for the external casing, and the half of the expansion angle γ_2 is determined as a function of known H_1 value and fixed R_2^{up} and R_2^{low} values.

Section III. Assuming inelastic collision of the recycled particles with the conical bottom of the SLVG, we shall introduce into the calculation the restitution coefficient K, which takes account of the decrease of the angle of rebound from the barrier and of the recycled particles motion velocity after the collision relative to the initial values [4]:

$$K = W_2 / W_1 = \tan\alpha' / \tan\alpha. \tag{16}$$

Then, the time τ_{III} of the recycled particles motion between the points B and C is determined by Eq. (13) at $\tan\alpha' = \tan(2\gamma_3 - 90)/K$, $W_2 = W_1 K$, and the fixed design value of H_3.

The maximum recycled particles flight distance is determined by Eq. (14).

Considering a lack of reference data on the restitution coefficient for collision of the recycled particles (ammonium nitrate) against a steel surface, the restitution coefficient $K = 0.44$ was determined experimentally as a function of the height of vertical fall of the recycled particles h_f and the height of its rebound from the steel surface h_r using the equation $K = (h_r/h_f)^{1/2}$.

Section IV. In the pneumatic transport mode, the second critical gas stream velocity v_{eq} (climb and entrainment rate) can be determined by the equation [7]

$$v_{eq} = 1.63\sqrt{\rho_{gr} g r / (\psi \rho_{gas})}, \tag{17}$$

where ρ_{gr} and ρ_{gas} are the granule and gas stream densities, kg/m^3; r is the granule radius, m; ψ is the coefficient of aerodynamic resistance of the particle to the gas flow.

The minimum volume gas flow rate that ensures pneumatic transport of the recycled particles through the central pipe of diameter $d_{c.p}$:

$$Q = \frac{4 v_{eq}}{\pi d_{c.p}^2}. \tag{18}$$

Assuming that the recycled particles move through the central pipe with velocity $W_3 \approx v_{eq}$ uniformly, we shall determine the motion time as

$$\tau_{IV} = H_{c.p} / W_3. \tag{19}$$

According to calculation, the recycled particles circulation time under different initial conditions of granule flight from the internal casing ranges from 2 to 4 sec in the case of free motion of the recycled particles in still air. Thus, internal recycled particles circulation is realized within a fairly short time, which ensures quick return of the recycled particles to the working zone of the SLVG. In such a pattern of motion of recycled particles, it is impossible to perform additional operations (cooling, heating, moisture removal, etc.) with them, which makes it necessary to install additional equipment for implementing these processes.

Unique solutions, which make it possible to combine internal circulation and thermal treatment of recycled particles, have been derived. These solutions differ only in how the movement of recycled particles is organized in the interannular space of the SLVG, so in further description attention will be focused only on one section.

Fall of recycled particles into ascending air stream. The recycled particle residence time in the interannular space can be lengthened by raising the gas phase velocity to the permissible maximum, at which the particle motion slows down. Experimental studies showed that the permissible maximum is $(0.65–0.75)v_{eq}$. At a higher gas stream velocity (considering polydispersity of the recycled particles), the particles are found to be carried off with the effluent gases beyond the SLVG.

Varying the size of the free section of the gas distribution grate as a ratio of the areas of the holes in the grate S_h to the total area of the grate S_g, i.e., $\delta = S_h/S_g$, can be proposed as one of the mechanisms of control of the recycled granules residence time in the interannular space. In the case of cooling of recycled granules or heating (possibly also drying) of thermally stable materials, the free section size must be chosen on the basis of the condition that the gas stream velocity is within $(0.65–0.75)v_{eq}$. For heating and (if necessary) drying of granules of thermally stable materials, the free section size is determined on the basis of the condition of the minimally required recycled granule heating time at which the structure of the core remains intact.

The results of study of the recycled particles residence time τ in the interannular space as a function of gas stream velocity v (in dimensionless coordinates $v/v_{eq}–\tau/\tau_{II}$) are plotted in Fig. 4. The v_{eq} value was calculated for the average recycled particles diameter. When the free section of the interannular space is controlled by varying the internal cone expansion angle and the shape of the external casing, the granule residence time cannot be controlled in a wide range. The cited results of the experimental studies indicated that the recycled particles residence time in the interannular space also cannot be increased substantially because of the action of counterflow of air on the recycled particles. The recycled particle fall rate can be reduced by placing inserts in the form of perforated ledges, which also ensure multistage contact of the recycled particles with the heat carrier.

Motion of recycled particles in multistage contact with heat carrier. An approach based on development of the mechanism of particle motion time control by varying the number n of ledges and their design (length L_s, slope angle γ_4, and perforation degree δ) was proposed in [15]. Because of the design variation, the gas stream velocity v_{os} in the above-ledge space varies. Taking the velocity difference $\Delta v = v_{eq} - v_{os}$ as a characteristic that affects the recycled particle motion time on the ledge, we shall calculate the recycled particle motion time by the equation

$$\tau_s = \frac{L_s}{\Delta v \sin \gamma_4}. \tag{20}$$

Calculation by this equation showed that the recycled particle residence time on the ledge is 2–20 sec, depending on the ledge design and the gas stream velocity.

The recycled particle residence time in the interannular space (when $W_{os} = v_{os}$ and $\alpha = 90 + \gamma_4$) can be determined with fair precision by an equation similar to (13):

$$-H_{is} = W_{os} \sin \alpha \tau_{os} - g\tau_{os}^2 / 2. \tag{21}$$

The total recycled particle residence time in the interannular space

$$\tau_{II} = n\tau_s + (n-1)\tau_{os}. \tag{22}$$

The results of the analytical solution of the equations of the mathematical model can be used to design SLVG with internal circulation of recycled particles, which can be organized in various ways, depending on the need for simple recirculation or for additional stages for heat treatment of the recycled particles during the recirculation.

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