

MATHEMATICAL RESEARCH ON VORTICAL HYDRODYNAMICS OF HYDRO-PNEUMATIC SEPARATOR

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Summary. The mathematical model of the hydrodynamic field of vortical motion of homogeneous and continuous medium has been developed, and the dynamics of heavy and easy particles of seminal technological mass in the centrifugal field of hydro-pneumatic separator has been determined.

Key words: hydro-pneumatic separator, processing of seed, vortical hydrodynamics, the Navier-Stokes equation

INTRODUCTION

At present, the industry of production of seed of vegetable and gourd cultures in Ukraine is one of the least mechanized and most labour consuming. The problem of lack of equipment, which exists in the industry of mechanization of processes of obtaining the seeds needs the solution by means of creation of new highly productive machines for the economies of different forms of management (specialized seed producing enterprises, industrial producers of vegetable and gourd products as well as small farmer economies).

The development of technological equipment for the mechanized process of obtaining the seeds of vegetable and gourd cultures includes deep analytical research of all the processes which take place in a machine, in order to make a correct choice of its technological parameters, construction and working organs.

The majority of existent technological lines and equipment used at present lose the substantial amount of seed and technological seminal mass which can be utilized after the completion of technological process. The problem of processing the technological mass is urgent enough, taking into account the increase of economic efficiency of the process of obtaining the seeds of vegetable and gourd cultures, the losses reaching 20% [1] of the amount of all the selected seed. One of the elements of solution of this problem is the necessity of theoretical grounding of the process of obtaining the seeds of melon and cucumber with the purpose of confirmation of theoretical pre-conditions.

OBJECTS AND PROBLEMS

The choice of a separator for the technological line of obtaining and processing the seeds depends on the physical, mechanical, size and mass properties of both garden-stuffs and ground seminal mass with seeds.

Conducting of analytical and theoretical research on literary sources [1, 3] made it possible to define the basic methods of separation (hydraulic, pneumatic, mechanical, combined) that provide the efficient extraction of seeds from vegetable and gourd cultures.

Each of these methods of separation has its advantages and disadvantages. But the quality of the obtained seed will mainly depend on the accordance of the selected method of separation of the ground mass with the biological features of culture. The machine [2] offered by the authors for obtaining the seeds and the processing of technological mass of vegetable, melon and gourds cultures will realize the combined method of separation combining two methods: hydraulic and pneumatic (Fig.1.), that allows to achieve a high degree of cleaning melon and cucumber seeds in the composition of a technological line. Examining the hydraulic method of separation of freshly extracted seed, it is possible to notice that the hard particles of the seminal technological mass, being in the stream of liquid that is revolved in a chamber, are subjected to the actions of centrifugal force. Thus, the particles of a greater volume mass (standard seed as a rule) are carried to periphery, and the particles of less volume mass (particles of peel, pulp non-standard seeds and other inclusions) rise and go out through the weathering opening as wastes. A pneumatic method provides intensive friction of layers of liquid due to barbotation, which enables to wash out mucus and jelly-like film and guarantee the best cleaning of seed of vegetable and gourds cultures (melon and cucumber) in a hydro-pneumatic separator.

The construction of the separator with the circuitous supply of water is more rational in comparison with the existing ones from the point of view of technical and economic approaches to its estimation.

In spite of the simplicity of the construction, the mathematical model of work of the separator is complicated enough, therefore we will conduct the analytical research in two stages. On the first stage, we will determine the hydrodynamic field of vortical motion of homogeneous and continuous medium with some density, and on the second one, the actual dynamics of heavy (standard seed) and easy particles (pulp, empty seed and other inclusions) in the centrifugal field of liquid. For the determination of optimum structural parameters of the separator, it is necessary to explore the process of work of the separator depending on the amount of water supply and pressure, circle rate of movement of stream and speed of weathering of liquid medium.

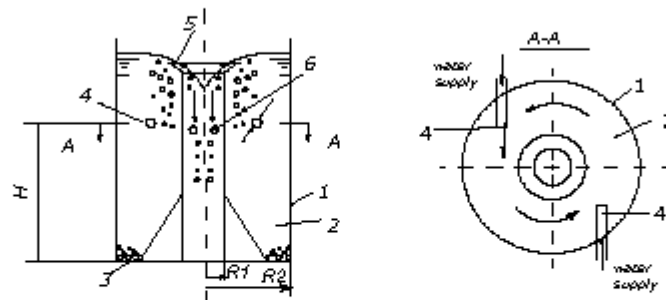


Fig. 1. Hydro-pneumatic separator:
Body of separator; 2. Water with particles of fruit, seed etc.; 3. Seed; 4. Tubes for water supply;
5. Weathering funnel; 6. Wastes.

The research on the processes which take place in a machine with the circuitous supply of water are described in the works of many scientists [4, 5, 6]. In the cylinder system of coordinates, the motion of such medium in a general view is described by the system of the Navier-Stocks equations [4]. However, the research on vertical hydrodynamics in a viscid liquid with seminal technological mass has not been done yet.

RESULTS OF RESEARCH

On the first stage, a liquid medium with different inclusions is considered homogeneous, viscid and incompressible one. It is known that the motion of such medium in a general view is described by the system of the Navier-Stocks equations, which in the cylinder system of coordinates (r, z, ϕ) looks like:

$$\begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{v}{r} \frac{\partial u}{\partial \phi} + \frac{v^2}{r} + w \frac{\partial u}{\partial z} - F_r - \frac{1}{\rho} \frac{\partial p}{\partial r} + \nu \left[\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u^2}{r} + \frac{1}{r^2} \frac{\partial^2 u}{\partial \phi^2} - \frac{2\partial v}{r^2 \partial \phi} + \frac{\partial^2 u}{\partial z^2} \right], \\ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial r} + \frac{v}{r} \frac{\partial v}{\partial \phi} + \frac{u v}{r} + w \frac{\partial v}{\partial z} - F_\phi - \frac{1}{\rho r} \frac{\partial p}{\partial \phi} + \nu \left[\frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} - \frac{v}{r^2} + \frac{1}{r^2} \frac{\partial^2 v}{\partial \phi^2} - \frac{2}{r^2} \frac{\partial u}{\partial \phi} + \frac{\partial^2 v}{\partial z^2} \right], \\ \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial r} + \frac{v}{r} \frac{\partial w}{\partial \phi} + w \frac{\partial w}{\partial z} - F_z - \frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left[\frac{\partial^2 w}{\partial r^2} + \frac{1}{r} \frac{\partial w}{\partial r} + \frac{1}{r^2} \frac{\partial^2 w}{\partial \phi^2} + \frac{\partial^2 w}{\partial z^2} \right], \end{aligned} \tag{1}$$

where: u, V, w - accordingly radial, circuitous and axial speeds; ν - kinematics viscosity, ρ - density of liquid; F_r, F_ϕ, F_z - projections of mass forces on the axis of coordinates; t - time; p - pressure.

The system of equations of motion (1) should be added by the equation of indissolubility for incompressible liquid:

$$\frac{\partial u}{\partial r} + \frac{u}{r} + \frac{1}{r} \frac{\partial v}{\partial \phi} + \frac{\partial w}{\partial z} = 0. \tag{2}$$

We break up all region of motion of liquid medium in two parts: below the feed pipes and above the feed pipes. In a lower region, the motion of liquid changes along the axis of z and at $z=0$, we consider that the medium is at rest. In an overhead region, we consider that the medium moves with identical axial speed along the coordinate z .

First of all, we consider the motion of liquid in a lower region. Due to the permanent mode of motion of mass the time derivatives are equal to zero $\left(\frac{\partial}{\partial t} = 0 \right)$. Taking into account the axial and symmetrical character of construction of the hydro-pneumatic separator, we consider that the derivatives on the coordinate (the angle) ϕ are equal to zero. The mass forces are also equal to zero, thus $F_r = F_\phi = F_z = 0$. Further, due to a low value, we ignore the axial and radial motion of liquid. As a result of the accepted assumptions the system of equations (1), (2) will look like:

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} - \frac{V}{r^2} + \frac{\partial^2 V}{\partial z^2} = 0, \tag{3}$$

where: r - radial coordinate $(R_1 \leq r \leq R_2)$;

z - axial upward coordinate, on which the point 0 is located in the center of the circle (bottoms of the separator) $(0 \leq z \leq H)$.

Equation (3) - should be followed by maximum terms:

$$V|_{r=R} = 0; \quad (4)$$

$$V|_{r=R} = 0; \quad (5)$$

$$V|_{r=0} = 0; \quad (6)$$

$$V|_{r=R} = f(r), \quad (7)$$

where: $f(r)$ - certain function of radius r

We search the solution of equation (3) by the method of division of variables, considering:

$$V(r, z) = V_1(r)V_2(z). \quad (8)$$

Putting (8) in to equation (3) and dividing the variables we will get:

$$\left[\frac{\partial^2 V_1(r)}{\partial r^2} + \frac{1}{r} \frac{\partial V_1(r)}{\partial r} - \frac{V_1(r)}{r^2} \right] \frac{1}{V_1(r)} = \frac{\partial^2 V_2(z)}{\partial z^2} \cdot \frac{1}{V_2(z)} = \lambda^2, \quad (9)$$

where λ - a constant value.

After the transformations of equation (9) we will get:

$$\frac{\partial^2 V_1(r)}{\partial r^2} + \frac{1}{r} \frac{\partial V_1(r)}{\partial r} + V_1(r) \left[\lambda^2 - \frac{1}{r^2} \right] = 0. \quad (10)$$

According to [5] the solution of equation (10) looks like:

$$V_1(r) = C_1 J_1(\lambda r) + C_2 Y_1(\lambda r), \quad (11)$$

where $J_1(\lambda r)$, $Y_1(\lambda r)$ - the Bessel's functions;

C_1 , C_2 - permanent integrations.

If we accept that $R_1 = 0$, then from (11) it follows that $C_2 = 0$. As a result, from a maximum condition (5) we have:

$$V_1(R_2) = C_1 J_1(\lambda R_2) = 0. \quad (12)$$

But as $C_1 \neq 0$,

$$J_1(\xi_n) = 0, \quad (13)$$

where: ξ_n - zeros of function $J_1(\xi_n)$, $\xi_n = \lambda_n R_2$.

Further, determining ξ_n we will use the approximation to $\xi > 1$ [6, 7]:

$$J_1(\xi) \approx \sqrt{\frac{2}{\pi \xi}} \cdot \cos\left(\xi - \frac{3}{4}\pi\right). \quad (14)$$

Then, according to (13) we get, that

$$\cos\left(\xi_n - \frac{3}{4}\pi\right) = 0 \quad \text{and} \quad \left(\xi_n - \frac{3}{4}\pi = \frac{\pi}{2} + \pi n\right), \text{ from which we find:}$$

$$\xi_n = \frac{\pi}{4}(1+4n), \quad n = 1, 2, \dots$$

Consequently,

$$\lambda_n = \frac{\xi_n}{R_2} = \frac{\pi}{4R_2}(1+4n). \tag{15}$$

Taking into consideration the obtained results (14), (15) with (10) we will get:

$$V_n(r) = C_n J_1(\lambda_n r), \tag{16}$$

where C_n - constant value.

Further, with (8) we have:

$$\frac{d^2 V_2(z)}{dz^2} - \lambda_n^2 V_2(z) = 0, \tag{17}$$

where $V_2|_{z=0} = 0;$
 $V_2|_{z=H} = 1.$

The solution of borderline task (17) looks like:

$$V_2(z) = \frac{sh[\lambda_n z]}{sh[\lambda_n H]} \tag{18}$$

where $sh[\lambda_n z]$ - function of hyperbolic sine.

Summing up all the specific solutions we have $V_n(r, z) = V_{1n}(r)V_{2n}(z)$, where $V_{1n}(r)$ is (16), and $V_{2n}(z)$ is (18).

Consequently, the solution of borderline task (3) – (7) will look like:

$$V_1(r, z) = \sum_{n=1}^{\infty} C_n(r) \cdot J_1(\lambda_n r) \cdot \frac{sh(\lambda_n z)}{sh(\lambda_n H)}. \tag{19}$$

For obtaining the approximate value of vortical flow, we will be limited in (19) by one member of the row and adopt $n=1$:

$$V_n(r, z) = C_{11} \cdot J_1\left(\frac{5\pi r}{4R_2}\right) \cdot \frac{sh\left(\frac{5\pi}{4R_2}\right)z}{sh\left(\frac{5\pi}{4R_2}\right)H}. \tag{20}$$

At $z=H$ with (19) we have:

$$V(r, H) = f(r) = \sum_{n=1}^{\infty} C_n(r) \cdot J_1(\lambda_n r).$$

On the other hand, according to [6], every continuous function that has the continuous first and second derivatives and fulfills the maximum conditions of task (here to term (4) and (5)) can be arranged in a row that evenly meets:

$$f(r) = \sum_{n=1}^{\infty} b_n \cdot J_1\left(\lambda_n \frac{r}{R_2}\right),$$

b - a constant value here .:

We consider that in our case:

$$f(r) \approx b_n \cdot J_1(\lambda_n r). \quad (21)$$

Equating the charges of liquid (water) from two tubes and according to (21), we will find the amount of water supply Q :

$$Q \approx 2 \frac{\pi d^2}{4} v_0 \approx b_n \delta \int_0^{R_2} J_1(\lambda_n r) dr, \quad (22)$$

where: δ - conditional thickness of the flat flooded stream in a dim stream;
 V_0 - speed of stream flowing from a tube; d - diameter of tube.

From (22) we have:

$$b_n = \frac{d^2}{4\delta \int_0^{R_2} J_1(\lambda_n r) dr} V_0 \frac{5\pi d^2}{16R_2\delta}. \quad (23)$$

For the field of circuitous speed in a separator now we get the following presentation:

$$V(z, r) = V_0 \frac{5\pi d^2}{16R_2\delta} J_1\left(\frac{5\pi}{4} \frac{r}{R_2}\right) \frac{\operatorname{sh}\left(\frac{5\pi}{4R_2} z\right)}{\operatorname{sh}\left(\frac{5\pi}{4R_2} H\right)}. \quad (24)$$

We consider that $\frac{5\pi d^2}{16R_2\delta} \approx 1$, then (24) looks like

$$V(z, r) \approx V_0 J_1\left(\frac{5\pi}{4} \frac{r}{R_2}\right) \frac{\operatorname{sh}\left(\frac{5\pi}{4R_2} z\right)}{\operatorname{sh}\left(\frac{5\pi}{4R_2} H\right)}. \quad (25)$$

In Fig. 2 and Fig. 3 the dependence is represented as:

$$\frac{V(z, r)}{V_0 \cdot J_1\left(\frac{5\pi}{2 \cdot 4}\right)} = \frac{\operatorname{sh}\left(\frac{5\pi}{4R_2} z\right)}{\operatorname{sh}\left(\frac{5\pi}{4R_2} H\right)}.$$

The maximum circular speed of stream is achieved at $z=0$ and $r = R_2/2$.

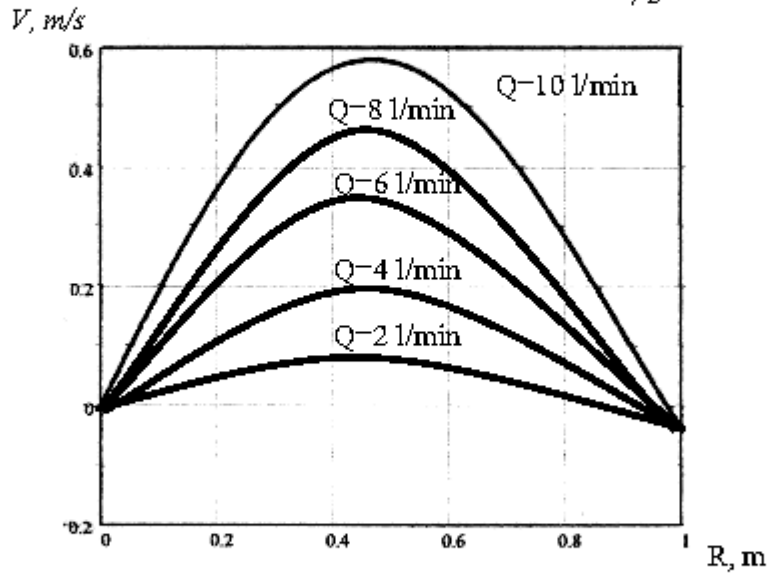


Fig. 2. Dependence of circular speed on the radius of capacity of hydro-pneumatic separator at a different amount of water supply

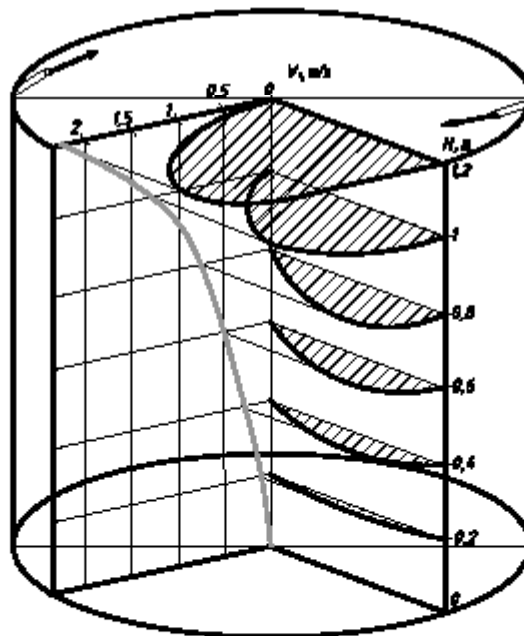


Fig. 3. Dependence of circular speed on the capacity of hydro-pneumatic separator

The seed of melon can be approximately examined as triaxial ellipsoid (Fig. 4) with semiaxes:

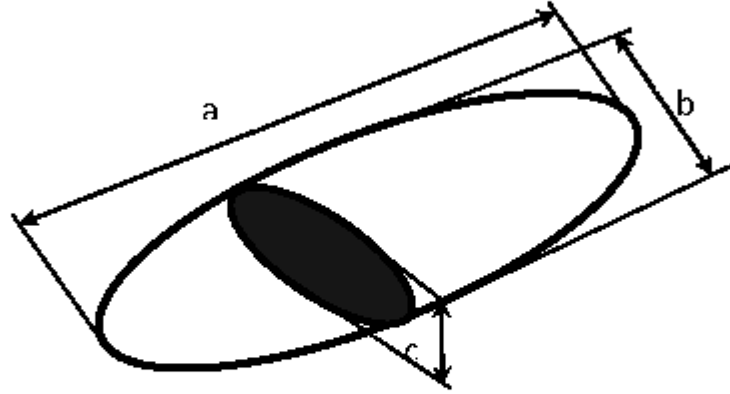


Рис. 4. Черт. семени арбуза

We accept: $a_{\text{med}} = 11,4 \text{ mm}$; $b_{\text{med}} = 5,5 \text{ mm}$; $c_{\text{med}} = 1,6 \text{ mm}$; then the volume of ellipsoid is equal to:

$$V_{\text{med}} = \frac{4}{3} \pi \cdot a_{\text{med}} \cdot b_{\text{med}} \cdot c_{\text{med}} \approx 425 \text{ mm}^3 = 0,425 \text{ cm}^3. \quad (26)$$

Radius of medium equivalent on volume:

$$r_0 = (a_{\text{med}} \cdot b_{\text{med}} \cdot c_{\text{med}})^{1/3} = 4,66 \text{ mm} = 0,466 \text{ cm}. \quad (27)$$

Mass of pip (equivalent medium):

$$m_e \approx \rho_e \cdot V_e \quad (28)$$

where ρ_e - density [$m_e \approx 0,6 \text{ g}$].

Developing the mathematical model of pip dynamics further we will examine the dynamics of the ball equivalent to it. The ball, being in hydro cyclone, will take part in two motions: falling and radial moving. Falling of the ball was explored in detail earlier [4, 6]. The radial motion will be caused by centrifugal force:

$$F_1 = \frac{4}{3} \pi r_0^3 (\rho_e - \rho_l) \frac{V^2}{r}, \quad (29)$$

where V is circuitous speed of stream of liquid medium; ρ_l - is density of liquid; r is radial coordinate of the ball.

At relative motion in a liquid the ball experiences the resistance:

$$F_2 = 6 \pi \eta r_0 \frac{dr}{dt}. \quad (30)$$

The equation of motion of ball in radial direction looks like:

$$\frac{4}{3} \pi r_0^3 (\rho_e - \rho_l) \frac{d^2 r}{dt^2} - \frac{4}{3} \pi r_0^3 (\rho_e - \rho_l) \frac{V^2}{r} = 6 \pi \eta r_0 \rho_l \frac{dr}{dt}. \quad (31)$$

Examining the permanent motion, we get:

$$6\pi\nu r_0 \rho_l \frac{dr}{dt} = \frac{4}{3}\pi r_0^3 (\rho_c - \rho_l) \frac{V^2(r)}{r}. \tag{32}$$

Dividing the variables in(32), we will write down:

$$\frac{r dr}{V^2(r)} = \frac{2 r_0^2}{9 \nu} \left(\frac{\rho_c - \rho_l}{\rho_l} \right) dt. \tag{33}$$

Integrating (33), we will find the time of radial way:

$$t_c = \frac{9\nu}{2r_0^2} \left(\frac{\rho_c - \rho_l}{\rho_l} \right) \int_0^R \frac{r dr}{v^2(r)}. \tag{34}$$

The time must be equal to the time of ball falling to the bottom of the plant.

We will mark that in (34) the circuitous speed depends not only on a radial coordinate but also on z, therefore, an approximate estimation of time of the radial way includes some mean value of speed on a height (the depth).

At this time the particles of peel must emerge to the free surface of liquid in the separator and get to the weathering funnel. However, this process goes faster, as the growth of bubbles and radial motion of weathering «helps» the flowing. For determination of the parameters of weathering, the chart of weathering of liquid medium over the edge of the funnel is presented in Fig. 5.

The basic parameters of the permanent motion of weathering are the height of raising of liquid above the edge of the funnel (h) and the speed of motion of medium (u₀). The analytical solution of this task is not available yet [7]. Therefore, we will apply the approximate solution.

We will write down the equality (equation) of the liquid expenses by finding Q₁ and charges of weathering over the edge of funnel Q₂:

$$Q_1 = \pi (R_2^2 - R_1^2) \cdot w_0; Q_2 = 2\pi R_1 h u_0, \tag{35}$$

where: w₀ - is average speed of liquid rise.

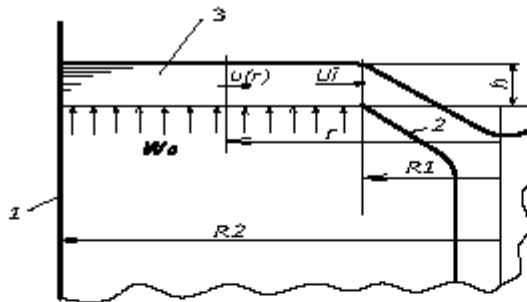


Fig. 5. Chart of weathering of liquid over the edge of funnel: 1 - wall of tank of hydro-pneumatic separator; 2 - funnel; 3 - liquid

Common decision (35) at Q₁ = Q₂ gives a correlation:

$$w_0 (R_2^2 - R_1^2) = 2 h u_0. \tag{36}$$

For the arbitrary coordinate r we will get the expression for radial speed:

$$u(r) = u_0 \frac{R_2^2 - r^2}{R_2^2 - R_1^2}. \tag{37}$$

We will find the kinetic energy of radial motion of liquid in the layer h :

$$K = \pi \rho_l h \int_{R_1}^{R_2} r u^2(r) dr = \frac{\pi \rho_l h u_0^2}{(R_2^2 - R_1^2)^2} \int_{R_1}^{R_2} r (R_2^2 - r^2)^2 dr. \quad (38)$$

Calculating the integral in (38), we get:

$$K = \frac{\pi}{6} \rho_l h (R_2^2 - R_1^2) \cdot u_0^2. \quad (39)$$

The potential energy of the layer of liquid above the level of funnel

$$P = \pi \rho_l g (R_2^2 - R_1^2) \cdot \frac{h^2}{2}. \quad (40)$$

The sum of kinetic and potential energies:

$$E = K + P = \frac{\pi}{2} \rho_l (R_2^2 - R_1^2) \cdot \left[g h^2 + \frac{1}{3} h u_0^2 \right]. \quad (41)$$

We will find the height of raising of liquid above the edge of the funnel:

$$h = \frac{Q_0}{2\pi \cdot R_1 \cdot u_0}, \quad (42)$$

where $Q_0 = 2V_0 \cdot \frac{\pi d^2}{4} = Q_1 = Q_2$.

With (41) we will find:

$$E(u_0) = A \left(\frac{u_0}{2\pi R_1} \frac{g}{u_0^2} + \frac{u_0}{3} \right), \quad (43)$$

where $A = \frac{\rho_l Q_0}{2 u_0} \frac{1}{2\pi R_1}$.

In accordance with the principle of achievement of minimum of energy $E(u_0)$, we will find the value of u_0 from the condition of $\frac{dE(u_0)}{du_0} = 0$. The equation for the weathering speed of weathering is:

$$u_0 = \left(\frac{3 Q_0 g}{\pi R_1} \right)^{\frac{1}{3}}. \quad (44)$$

Then, for the height of the layer we will get from expression (42):

$$h = \frac{Q_0 g}{2\pi R_1 u_0} \left(\frac{Q_0^2}{24\pi^2 R_1^2 g} \right)^{\frac{1}{3}}. \quad (45)$$

Accepting $Q_0 = 0,5 \cdot 10^{-3} \text{ m}^3/\text{s}$; $g = 9,81 \text{ m}/\text{s}^2$; $R_1 = 0,05 \text{ m}$,

$g = 9,81 \text{ m}/\text{s}^2$; $R_1 = 0,05 \text{ m}$; we get $h = 5,5 \cdot 10^{-3} \text{ m} = 5,5 \text{ mm}$, $u_0 = 0,46 \text{ m}/\text{s}$.

CONCLUSIONS

The size of the centrifugal circular speed depends on the amount of water supply through the sprayers. With the increase of water supply from 2...10 l/min. the circular rate of the movement of stream grows from 0,1 to 0,7 m/s, which enables to accelerate the process of washing the seeds of vegetable and gourds cultures (melon and cucumber) in a hydro-pneumatic separator from mucus, pulp and other inclusions.

As a result of research and mathematical treatment of results of the model of circular motion of liquid, it was determined at what amount of water supply ($Q = 5...8$ l/min.) the most effective rate of movement of liquid medium ($V = 0,3...0,6$ m/s) is achieved.

The process of weathering of liquid compound medium (mixture of water, seed, juice, particles of peel and pulp) over the edge of funnel has been considered, that made it possible to define the calculation height of raising of liquid above the edge of funnel $h \approx 5,5 \cdot 10^{-2} \text{ m} = 5,5 \text{ m}$ and the speed of motion of medium $v_0 \approx 0,46 \frac{\text{m}}{\text{s}}$. The obtained values of parameters of h , v_0 correspond to those observed at the work of the plant and provide for the removal of wastes after the hydro-pneumatic separation of seed.

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MATEMATYCZNE OPRACOWANIE HYDRODYNAMIKI ODŚRODKOWEJ
HYDRO-PNEUMATYCZNEGO SEPARATORA

Streszczenie: Opracowano model matematyczny oczyszczania i separacji nasion dyni przy pomocy separatora hydrauliczno-pneumatycznego. Metoda pozwala oddzielić frakcje cząstek ciężkich od lekkich w nasionach, wykorzystując siłę odśrodkową.

Słowa kluczowe: siła odśrodkowa, hydropneumatyczny separator, obróbka nasion, równanie Navier-Stoksa