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Mathematical modeling of theim pulse bubbling process of bulk mass by the coolant flow

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Abstract. The main directions of pneumodynamic system usage for storage of bulk agricultural products are bubbling and pneumatic mixing; loading and unloading of technological masses. During pneumodynamic impulse wave formation with alternation of supersonic and subsonic zones, which are limited by shock waves, sound force increasing on the technological mediumabout 150…170 dB, pressure increasing on the product mass due to compression-stretching at the pulse limits to amplitudes of 6…15 barare caused, that promotes implementation of loosening processes during the grain material storage.The developed scheme of the studied process involves the opposite arrangement of pneumatic impulse generators, which allows the formation of a stationary wave,that spreads the pulse energy in both longitudinal and transverse directions, covering the maximum space of the free flowing technological medium. Using the method of D'Alembert for solving the equations, methods of mathematical analysis and their processing in the MathCAD mathematical environment graphical and analytical dependences of force parameters of oscillatory system have been obtained. Choosing an effective mode of pneumodynamic loosening, the force pulse magnitude and the regularities of its change under conditions of the highest mechanical resistance of the free-flow mass have been used as the evaluation criteria the standing wave energy.

1. Introduction

One of the effective means of damage leveling and seed deteriorating of grain products through caking [1], microbiological damage during storage is the regular bulk shifting and loosening [2]. Mechanical tools in the form of screw [3], auger and other mixing actuators are typically used to implement this process [4].

For agitating bulk materials stored in warehouses [5], mechanical screw-type agitators are used, the operation of which is characterized by high energy and material costs [6]. The use of pneumatic mixing of products in facilities with airlift can significantly reduce energy consumption, but is characterized by insufficient efficiency of layer-by-layer movement of grain products [7]. Pneumatic agitator systems do not involve product contact with mechanical working bodies [8], have the ability to act on large arrays of products [9], featuring by simplicity of mechanization and automation modes of operation and regulation of technological action parameters [10]; however, they are properly efficient mainly in transport systems [11], and the mixing processes with high energy dissipation of grain masses [12] are characterized by sufficiently high energy costs for the process with insufficient efficiency of loosening over the product layers[13].

Pneumodynamic systems with variable working pressures [14], characterized by the formation of a pulsed wave [15], allow to increase the action efficiency on bulk dispersed medium: first, the formation of a ball-shaped kernel of a wave occurs under the conditions of increasing static pressure along the air flow [16], then there is a promotion of a non-stationary gas jet with alternation of supersonic gas streams which are limited by shock waves [17]. Thus there is the sound force increasing on the technological medium about 150...170 dB [18], the effect of force action on the production mass increases due to compression-stretching at the pulse limits with an amplitude of 6...15 bar [19], which contributes to the efficient implementation of the loosening processes [20].

2. The aim and objective of research

The objective of the conducted researches is the theoretical substantiation of the operating mode parameters of the pneumatic impulse agitating of grain products during the warehouse storage under the conditions of effective spatial mixing of the bulk mass while minimizing energy consumption to create and maintain the oscillatory process.

To accomplish this objective, the following tasks are to be performed:

- development of conceptual and computational scheme of the process of pneumatic impulse bubbling of bulk medium;
- method of obtaining analytical dependencies and their graphical interpretation for the force parameters of the developed pneumodynamic agitator;
- theoretical substantiation of the number of pneumatic impulse flows to ensure the studied process efficiency.

3. Materials and methods

When conducting the theoretical analysis [21] and substantiation of the mode characteristics of the developed pneumatic impulse moving agitator [22], we have used the "string theory" [23].

The method of D'Alembert for solving these equations [24], the methods of mathematical analysis and their processing in the MathCAD [25] mathematical environment to obtain the necessary graphical and analytical dependencies of the basic system parameters [26].

4. Research results and their discussion

The developed pulsating grain mass agitator combines the positive features of the equipment presented above.

Its main elements are pallets 1 (figure1a) for placing products, an air pressure pulse generator, collectors for distribution of pneumatic streams to a loose medium. The presence of the diaphragm and elastic elements ensures periodic cutting and sealing of the pneumatic chamber with the fan outlet. Grain products are placed in pallets at a certain distance from the floor, which significantly reduces the possibility of moisture accumulation in the lower layers and facilitates access to the loading and unloading facilities.

Operating with such a pneumatic impulse agitator, the compressed air under the pressure of P_1 = 0.2…0.3 MPa is fed to the working pneumatic chamber, the pressure in which increases rapidly and

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presses the diaphragm to the saddle, the speed and force of clamping to which are determined by the rigidity of the elastic elements. When the required pressure is reached, the diaphragm moves away from the saddle and passes the air to the nozzle at the inlet to the manifold. The generated air flow pulse generates a pneumodynamic wave in a dispersed medium in the axial direction. After equalizing the pressure, the spring returns the diaphragm to the annular saddle. The compressed air is fed into the working pneumatic chamber continuously, which ensures the cyclicity of the presented pressure pulse generation process.

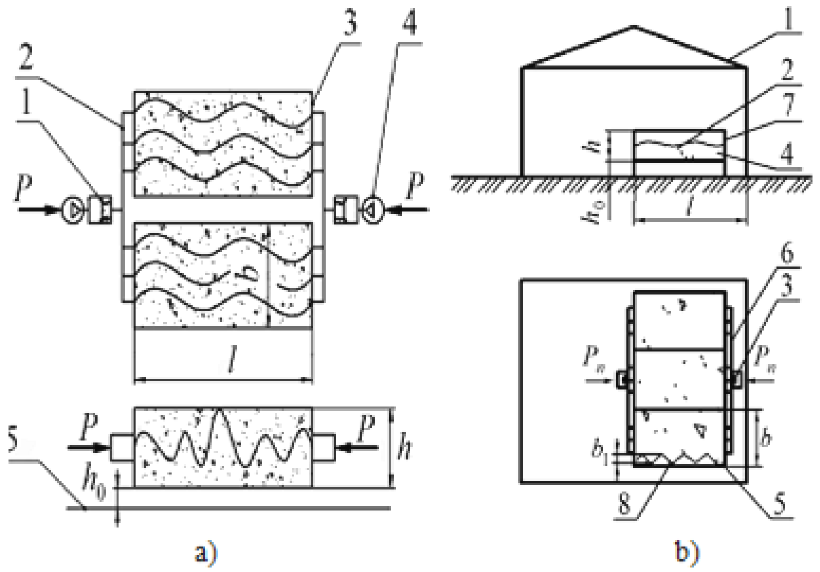


Figure 1. Pneumatic impulse agitator: a – schematic diagram: 1 – pneumatic impulse bubbler; 2 – collector; 3 – pallet; 4 – fan; 5 – floor; b – scheme of arrangement of pallets with products during the warehouse storage: 1 – granary; 2 – pallet with products; 3 –pneumatic impulse generator (bubbler);
4 – grain mass; 5 – processed layer of products; 6 – collector; 7 – rack; 8 – working pneumodynamic wave.

However, the formed dynamic wave is characterized by low efficiency of grain mass loosening in the radial direction, so it is expected to create counter-pneumatic waves from oppositely located pulse bubblers (figure 1b), through the superposition of counter waves it allows to create a standing wave that can transmit energy both longitudinally and transversely. The coordinate placement of pneumatic flow sources along the plane and height of the pallets makes it possible to agitate efficiently in the specified product arrays.

Carrying out mathematical modelling of this impulse bubbling process, the opposite position of the developed impulse generators has been takenas a basis(figure 2). It allows to generate waves with equal amplitudes of force factors with the same or approximate driving force, which form a standing wave even with a certain deviation of the initial phases under the superposition. The features of the standing wave are:

- the particles of the medium do not move with the wave but oscillate around their equilibrium positions;
- at nodal points energy is not transmitted, and within a distance of half of the wavelength, the wave kinetic energy is converted into the potential energy of particles interaction of the product bulk mass;
- the formed wave exerts transverse oscillations in relation to the nodal points, which significantly accelerates the intensification process of the grain mass in both axial and radial directions.

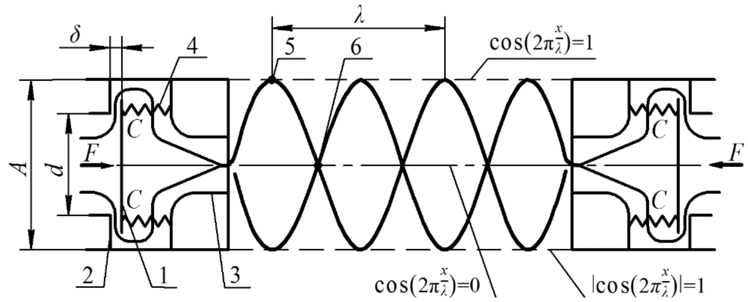


Figure 2. Diagram of pneumatic impulse bubbling process: 1 – diaphragm; 2 – diaphragm saddle; 3 –Laval nozzle; 4 – recovery elements; 5 – nonsense; 6 – nodes.

For the mathematical description of the impulse bubbling process the theory of "strings" has been used, according to which the wave one-dimensional equation of the process has the form:

$$\frac{\partial \cdot P}{\partial x} - \frac{1}{\vartheta_{\varphi}^2} \cdot \frac{\partial^2 P}{\partial \cdot t^2} = 0 \ , \tag{1}$$

where P (x,t) – a pressure function that performs and maintains the oscillatory process in a flowing medium;ϑ_{ϕ}– a phase velocity of wave propagation; x, t – process variables: respectively linear coordinate and wave propagation time.

The general solution according to the D'Alembert method and its interpretation for the studying process can be represented as a superposition of two harmonic waves:

$$P(x,t) = P_1 cos(k_1 x - \omega_1 t) + P_2 cos(k_2 x + \omega_2 t), \tag{2}$$

where P_1 ;P_2 – pressure amplitude values; $k_{1,} k_2$ –wave numbers: $k = \frac{\omega}{\sigma_{\varphi}}$; ω_1, ω_2 –cyclic frequencies of wave phase change; $\omega t = \varphi$–phase of the wave.

Under boundary conditions:$P(x,t) = 0, x = 0, \frac{d^2 \cdot P(x,t)}{d \cdot x^2} = 0$, as well as assumptions, that: $P_1 = P_2 = P_0$, $\omega_1 = \omega_2 = \omega$; the waves propagate without attenuation, possibly with some phase deviation, the differential wave equation becomes:

$$\text{P(x,t)} = 2P_0 sinkx \cdot sin\omega t \text{ or } P\ (x,t) = 2P_0 coskx \cdot cos\omega t\ . \tag{3}$$

The compelling force of the process is:

$$F_{\pi}(x,t) = 2F_{3M} sinkx \cdot sin\omega i\ , \tag{4}$$

where $F_{3M} = \frac{\Delta P}{S}$ –force of pressure, which is the driving force of this oscillatory process, which can be determined by the formula:

$$F_{3M} = \frac{F_n}{2sin\frac{2\pi}{\lambda} x \cdot sin\omega t}, \tag{5}$$

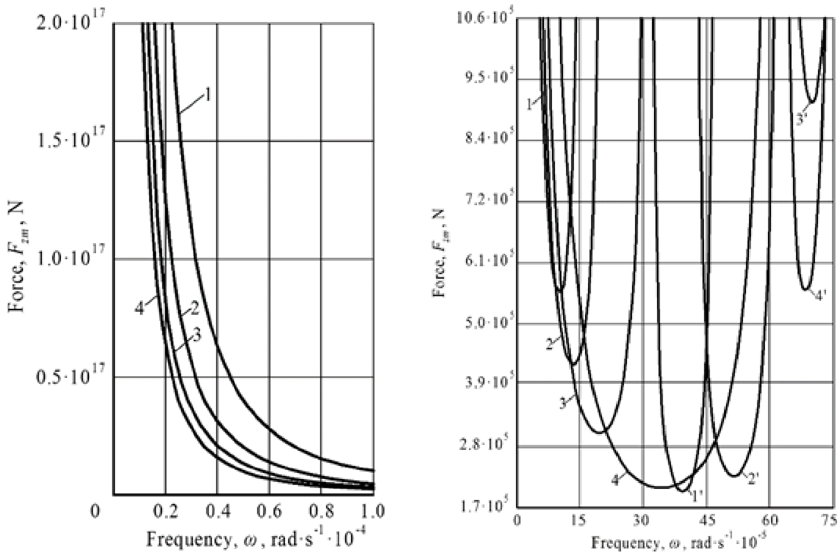
$$F_n = 0.3...0.5\text{MPa};\ \Delta P = P_3 - P_2.$$

Taking into account that the elastic force of the check valve $F_{\Pi P} = C_x \delta$, pressure P_3 is:

$$P_3 = \frac{4F_3}{\pi d_k^2} = \frac{4C_x\delta}{\pi d_k^2};\ P_1 = \frac{F_\pi}{S_k} = \frac{F_\pi \cdot 4}{\pi \cdot D^2},$$

where P_3 – diaphragm opening pressure.

In the MathCAD mathematical environment the main force characteristics of the pulsed pneumodynamic wave in the developed bubbler are presented in figure 3, which present the spectrum of pulse change of geometric parameters at different intervals of cyclic frequencies.



a) b)

Figure 3. Dependence of the pneumodynamic flow momentum on the cyclic frequency of phase change of the wave ω for the wavelength within the frequencies: a –ω = 0-10-4 rad/s; b–ω = 0…75 rad/s; 1 – wavelength t = 0.05 s; 2 – in t = 0.1 s; 3 – in t = 0.15 s; 4 – 0.2

The required number of pulsed pneumodynamic generators or bubblers for the effective agitation of the bulk mass in the pallets has been determined from the calculation of the corresponding resistance of the technological grain medium in the propagation of air flow dynamic waves in it according to the following formula:

$$P_{об} = k_{асп} \cdot \frac{h_{пр}}{d_{екв}} \cdot \frac{6 \cdot k_\rho \cdot k_\varphi}{(1-k_\rho)} \cdot \rho \frac{\upsilon_п^2}{2}, \tag{6}$$

where $k_{асп} = \frac{k_1}{R_e} + \frac{k_2}{R_e n}$– aerodynamic coefficient in the process for turbulent flow: $k_1 = 9$; $k_2 = 1$; $n = 0.16$;$d_{екв} = 6.0\ mm$ – equivalent grain diameter;$k_\rho = \frac{p_з}{p_н} = \frac{1330}{760} = 1.75$– density factor of the product mass;$p_з = 1.2 \ldots 1.5$ t/m³→ $p_з = 1330$ kg/m³ – grain mass density for wheat; $p_н = 730 \ldots 850$ t/m³→ $p_з = 760$kg/m³– bulk density of wheat products; $k_ф = 0.52$ – form factor for wheat; $\rho = 1.2255$ kg/m³ – air density; $\vartheta = 8.9 - 11.5$ m/s→ $\vartheta = 100$ m/s – air flow pulse rate.

As a result, the desired resistance, which constitutes a free flowing for air flow, is:

$$P_{оп} = 0.21 \cdot \frac{0.7}{6 \cdot 10^{-3}} \cdot \frac{6 \cdot 0.52}{(1-1.75)^3} \cdot 1.2255 \cdot \frac{10^2}{2} = 11.1 \cdot 10^3\ \text{H/m}^2.$$

Then the amount of air flow, that can be provided with one pneumatic impulse agitator, is defined as:

$$n_п = \frac{P_p}{P_{оп}} = \frac{0.9 \cdot 10^6}{11.1 \cdot 10^3} = \frac{900}{11.1} = 81\,\text{flow.}$$

where $P_p = 0.8...1.0$ MPa– operating pressure in the system.

5.Conclusions

As a result of mathematical modeling of the impulse bubbling process of bulk mass by the coolant flow, the efficiency of creating a standing pneumodynamic wave at the pulse generators opposite location has been found out, which allows to transfer kinetic energy of the flow both in the longitudinal and transverse directions, significantly intensifying its product agitating. The working pressure of the impulse bubbler should be within 0.3… 0.5 MPa and the pressure ratio of the opening and closing of the diaphragm of the pneumatic working chamber, should be respectively P_3= (3.5…5.0)P_2.

The spectrum of the geometric parameters change of fixed-length pulses at different intervals of cyclic frequencies has shown their parabolic nature and sufficiently close trajectories, which confirms the tendency of such waves to superposition at their counter-motion and high potential for process intensification of bubbling and stirring of grain-mass agitating; the most favourable parameters of the studied process are the wavelength of 0.2 s within the frequency range from 0… 100 rad/s.

The wave energy of two oppositely positioned pneumatic impulse generators is sufficient to overcome the resistance of the grain medium in 81 directions for one working capacity, which is reasonable to allow it to agitate efficiently the bulk mass with the flow of the coolant.

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