KAPITEL 2 / CHAPTER 2 [2]
DISCRETE-PULSE ENERGY INPUT IN TECHNOLOGIES FOR PROCESSING HETEROGENEOUS MEDIA USING ROTARY-PULSATION APPARATUS

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Introduction

Rotary-pulsation devices are widely used in various industries, primarily in basic technological operations of grinding, dispersion, emulsification associated with the homogenization of processed multicomponent fluid mixtures. Particularly promising is the use of these devices for the purpose of processing plant products and complex biological systems for the needs of the food, canning and pharmaceutical industries. Many years of experience in the creation, improvement and industrial operation of rotary-pulsation apparatus (RPA) of various modifications, accumulated at the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine, have proven the multi-vector nature of their practical application and the fundamental possibility of rational and reliable use for solving various technological problems [1].

Devices of this type have shown high efficiency when carrying out operations of mixing and homogenizing highly viscous mixtures, for example, for the production of water-fuel oil, water-fuel emulsions and cutting fluids, as well as when processing viscoplastic materials of plant origin [2-4]. Based on the modified design of the RPA, an innovative technology for preparing homogenized soybean paste for baby food has been developed and introduced into production, which is based on the thermal-moisture and rotary-pulsation processing of soybeans [4]. Microstructural analysis of the protein paste obtained using this technology showed that as a result of rotary-pulsation processing, the soybean structure is destroyed down to the cellular level [4]. This proves the extremely high level of dynamic effects created in the apparatus. Improvement of the technology for preparing wort from starch-containing raw

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materials in alcohol production using rotary-pulsation processing for ultra-fine grinding of grain [3] made it possible to achieve a significantly higher degree of grinding dispersion with a 30% reduction in energy consumption compared to that provided by traditional grinding devices (hammer, ball, roller-pendulum crushers).

The use of RPA in this technology made it possible to create force effects at the micro level, as a result of which starch grains, due to the destruction of internal intercellular connections, acquire the properties of soluble starch. Considering that the destructive forces during shear cleavage of starch-containing endosperm of wheat, barley, and corn grains (the main types of raw materials in this production) are measured in megapascals, and during longitudinal compression – in tens of megapascals [5], it is possible to quantitatively estimate the level of force effects that are initiated in RPA. The conducted experimental studies of the kinetics of the sucrose inversion process in the production of a glucose-fructose product using a rotary pulsation apparatus made it possible to reduce the duration of the technological process by almost 20 times and, due to this, significantly reduce energy and resource costs with an obvious improvement in the biological and organoleptic indicators of the finished product [6]. The data obtained as a result of the study that the main factors of intensification of the sucrose inversion process when using RPA are the temperature of the solution and the magnitude of shear stresses, allow us to draw a conclusion about the main physical mechanisms implemented in the device, which provide such a high degree of influence on the rate of chemical processes. The magnitude of the energy of breaking intermolecular bonds during sucrose inversion (1070 kJ/mol) allows us to judge the quantitative values of energy effects that are provided in the apparatus during the implementation of a specific mechanism. Various modifications of the RPA are widely used in drying technologies. Drying processes process a wide variety of liquid products, for example, in the pharmaceutical, food and chemical industries. In practice, the drying process is in most cases the final stage of the technological chain. Before being fed to the input of the drying chamber, the raw material (often plant and animal products or products of microbiological synthesis) is subjected to preliminary processing in order to grind it and increase the specific evaporation surface [7]. The high dispersing capacity of rotary-pulsation devices is effectively used in the processes of absorption of poorly soluble gases, primarily due to the creation of a very high specific surface area of phase contact [8, 9]. The main mechanism of dispersion of the gas phase is considered to be the fragmentation of gas bubbles under the action of shear stresses in a narrow gap between the rotor and stator [9]. Rotary-pulsation apparatus, used primarily for the intensification of hydromechanical and mass-exchange processes, can also be used as thermal energy generators [10]. According to the authors' calculations, the heat output coefficient, which is determined by the ratio of the total amount of heat released during the operation of the RPA to the energy expended, reaches 1,8. The efficiency value (the ratio of heat spent on heating the liquid in the heating circuit to the energy supplied to the input of the device) is 60...70%. Analyzing the operation of the rotary-pulsation device as a heat energy generator that ensures environmental safety, efficiency, industrial feasibility, reliability, and ease of operation, the authors consider the cavitation mechanism in the stator channels as the main reason for heat generation. Although the operating principle of rotary-pulsation apparatus has been known for several decades, and theoretical and experimental studies aimed at improving its design are conducted in many research centers, the question of the nature of the physical mechanisms that ensure high efficiency of its operation in various processes still remains open. It is generally accepted that the operation of rotary-pulsation apparatus is based on the principle of discrete-pulse energy input, which ensures a variety of physical mechanisms initiated during the operation of the device and the multifactorial nature of their impact on the processed product [1, 10, 11].

The purpose of this article is to analyze the mechanisms of discrete-pulse energy input, which are implemented in the working elements of the device during its operation, and to assess the effectiveness of each of these mechanisms in relation to solving specific technological problems using RPA.

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2.1. Mechanisms for intensification of hydromechanical processes of RPA

Let us consider the features of the operation of a rotary-pulsation apparatus in relation to solving problems of hydromechanical processing and homogenization of dispersed systems and the main factors that are used in the apparatus when solving these problems.

As a basic model of the RPA, we use a cylindrical device design consisting of three coaxially placed cylindrical elements: two stators and a rotor rotating between them. There are very narrow annular gaps between the rotor and the stator. On the surfaces of the stators and rotor, parallel to the rotation axis, with equal periodicity, there are narrow slotted holes of the same width, which mutually overlap when the rotor rotates. If there is liquid inside the device, the rotation of the rotor ensures tangential movement of the liquid in the annular gaps and, due to the action of centrifugal forces, its radial movement through the slotted holes of the rotor and stators.

The design characteristics of the basic model of the RPA are as follows [1]:

Distance of the inner surface of the rotor from the axis of rotation $R_{r1}=30\cdot 10^{-3}$ m.

Distance of the outer surface of the rotor from the axis of rotation $R_{r2}=34\cdot 10^{-3}$ m.

Thickness of rotor and stator walls $l= 4\cdot 10^{-3}$ m.

Width of slot on rotor and stator surface $a = 4\cdot 10^{-3}$ m.

Height of rotor and stator slot $h = 24\cdot 10^{-3}$ m. Distance between slots $b= 3\cdot 10^{-3}$ m.

Width of gap between rotor and stators $\delta = 0{,}15\cdot 10^{-3}$ m.

Number of slot openings on rotor (stator) surface $n = 30$.

Operating parameters:

Volumetric flow rate of the processed mixture $Q = 10^{-3}$ m^3/s.

Angular speed of rotor rotation $\omega = 47{,}5$ rpm = 298 rad/s.

Tangential velocity of the inner surface of the rotor $\nu_{\varphi 1} = \omega R_{r1} =$ 8,9 m/s.

Tangential velocity of the outer surface of the rotor $\nu_{\varphi 1} = \omega R_{r1} =$ 9,53 m/s.

Average value of tangential rotor speed $v_{\varphi} = (\nu_{\varphi 1} + v_{\varphi 2})/2$ = 9,54 m/s.

The designs of rotary-pulsation apparatus developed at the ITTF NASU, their dynamic and energy characteristics, features of flow distribution in devices, dissipative effects during mixture processing, examples of the use of RPA in the processing of highly viscous media and biological systems are considered in detail in the works [1]. This article aims to briefly analyze the role of the basic mechanisms of discrete-pulse energy input (DPEI), implemented in this device, in order to select optimal design options and process modes when solving specific process problems.

Let us consider how the above mechanisms of the DPEI are implemented in the working elements of the rotary-pulsation apparatus during its operation. Hydrodynamic processes in the channels of the internal stator The flow of the processed mixture flowing through the apparatus is repeatedly interrupted due to the mutual overlapping of the openings of the rotor and stator, with a periodicity of about 2 kHz. When the stator slots are overlapped by the rotor surface, the liquid in the slot channels of the stator is sharply slowed down. Time from the beginning of the hole blocking to complete blocking $\tau_1 = a/v_\varphi = 0{,}3$ ms, duration of full overlap $\tau_2 = (b-a)/v_\varphi = 0{,}1$ ms and the opening time of the holes $\tau_3 = a/v_\varphi = 0{,}3$ ms.

This cycle of changing the flow cross-section of the channel for the movement of liquid in the radial direction is repeated every 0,7 ms, so that during the operation of the device, the stage of full opening of the channel is actually absent. When the target opening is blocked and the associated sharp deceleration of the flow in the liquid in the channels of the first (internal) stator, high-amplitude pressure pulsations occur. In this case, the kinetic energy of the flow is periodically transformed into potential energy with the initiation of the phenomenon of hydraulic shock as an accompanying effect. In the slotted channels of the second stator, due to the sharp pressure drop when the channel closes and its rapid subsequent restoration during the opening process, high-speed powerful effects of explosive boiling and cavitation collapse are periodically created. The frequency and amplitude of these pulsations depend both on the rotor speed and on the number of slots and the flow rate inside the apparatus. The movement of liquid in the radial direction occurs in a pulsating mode, so that the linear velocity of liquid movement in the slot channels changes from the maximum value – $v_{r\max}$ to the minimum – $v_{r\min}$. The average value of the radial velocity $\bar{v}_r = Q/nah = 0{,}463$ m/s

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is significantly less than the tangential flow velocity in the gaps. The maximum achievable radial velocity v_{rmax} is determined by the channel overlap conditions and is equal to 1,08 m/s, which is an order of magnitude less than the tangential flow velocity at the rotor surface. The consequence of low values of the linear flow velocity is a comparatively low level of development of dynamic effects associated with the braking and acceleration of the flow and the accompanying effects of hydraulic shock. The magnitude of acceleration in channel I of the stator, during the closing and subsequent opening of the slot holes, is determined by the formula $|g_l| = (v_{r\,max} - v_{r\,min})/\tau_1$ and is $3{,}6 \cdot 10^3$ m/s^2. This is much less than the accelerations that are realized in such DPEI devices as a pulsating disperser with an active diaphragm or a vacuum emulsifier [12]. When the openings at the outlet of the channels I of the stator are quickly blocked, a hydraulic shock effect occurs in each of these channels. At the moment of complete opening of the channel, the liquid moves in the channel of length l with the speed v_{rmax} = 1,08 m/s and by the moment of complete blocking of the channel τ_1=0,3 ms it slows down to the value $v_{rmin} \approx 0$. As a result, a high-pressure pulse Δp is formed in the outlet section of the channel, which propagates towards the flow to the inlet section of the channel with the speed of sound u_{ac}, which depends on the properties of the processed medium. After a time interval $\tau=2l/u_{ac}$ (the so-called impact phase), the increased pressure is replaced by a vacuum, and during the time $\tau= 2l/u_{ac}$ the liquid is under low pressure. The period of pressure oscillations in the channel associated with the initiation of the phenomenon of hydraulic shock is determined by the value $\tau=4l/u_{ac}$.

If the continuous liquid phase is water, the period of pressure oscillation in channel I of the stator is 11,5 μm, and the impact phase lasts 5,7 μs. During the time of complete closure of the opening τ_2 = 0,1 ms, about ten pressure oscillations can occur in the channel. If the channel closure time exceeds the duration of the impact phase, an indirect hydraulic shock occurs, for which the amplitude of the pressure pulse depends on the ratio of the impact phase to the closure time and is determined by the formula $\Delta P = 2\rho_l \nu_{r\,max} l / \tau_1$. For the device under consideration, the oscillation amplitude is 0,028 MPa, and the frequency of damped oscillations is about 90 kHz. It is characteristic that with indirect hydraulic shock (as opposed to direct), the pressure amplitude does not depend on the speed of sound in the processed medium. At an average radial velocity of $\overline{v}_r$ =0,463 m/s, the liquid passes through the slot channel I of the stator in about 10 ms, and during this period of time, about 15 channel closures occur and, consequently, each element of the processed medium is exposed to the action of a hydraulic shock the same number of times. Although the amplitudes of pressure pulsations during hydraulic shock are relatively small, the continuity and high frequency of these pulsations undoubtedly make a certain contribution to the process of hydromechanical processing of the product.

2.2. Hydrodynamic processes in the channels of the outer stator

Qualitatively different phenomena are observed during periodic blocking of the holes in channel II of the stator. At the moment of combining the slotted holes of the rotor and stator in the channel of the outer stator, the speed of the liquid is maximum. When the holes are blocked, the flow of liquid into the stator channel slows down and then actually stops, since its insignificant flow occurs only due to the transit flow from the radial gap between the rotor and the stator. The liquid in the channel tends to exit the channel, and inertial forces create tensile stresses in it. As the channel empties, the pressure quickly decreases from normal to the pressure of saturated steam at the temperature of the environment, which causes explosive boiling of the liquid inside the channel. During the time $\tau_1+\tau_2$ = 0,4 ms, intensive growth of bubbles occurs, and in the initial stage the growth rate reaches 1000 m/s. When the hole opens, a high-pressure pulse enters channel I of the stator, which leads to the intensive collapse of a large set of bubbles with the release of a high-amplitude pressure pulse. As a result, in a short time the pressure increases to several atmospheres by the time the holes are subsequently closed. Thus, high-amplitude pressure oscillations constantly occur inside channel II of the stator with a frequency of about 2 kHz, resulting in a powerful hydroacoustic effect. Cavitation phenomena occurring in the stator channel and the accompanying phase transformations can be considered as acoustic cavitation, which is one of the most severe mechanisms of DPEI and which is widely used to intensify mass transfer and hydromechanical processes in dispersed media [11, 12]. The identity of the cavitation processes occurring in the external stator of the RPA and the phenomenon of acoustic cavitation is confirmed by experimental data. In [11], photographs of a cavitation cluster formed above an ultrasonic magnetostrictive emitter at a static pressure of 0,2 MPa and photographs of a cavitation cluster in the stator channel of a rotary-pulse apparatus are presented. The similarity of the shape and structure of both clusters gives grounds to assume the identity of the mechanisms of their formation and stabilization.

2.3. Shear flow in intercylinder gaps of RPA

Powerful pulsation effects are one of the main factors ensuring high efficiency of RPA in the processes of homogenization and grinding of various products, primarily structured products of plant and biological origin. No less important contribution, especially in crushing solid particles and emulsions, is made by the mechanism of shear stresses in narrow gaps between the rotor and stator. The linear velocity of the liquid being processed in the gaps changes from zero at the boundary with the stator surface to the value of the tangential rotation speed of the rotor at the boundary with its surface. In this zone of the device, the greatest dissipation of energy occurs, but it is precisely in this zone that the strongest destructive effect on dispersed particles occurs. The use of shear stresses in shear flows is one of the basic mechanisms of the DPEI, providing a hard effect on dispersed particles [13]. The force of interaction of a particle with a liquid is proportional to the gradient dv_φ/dr. The possibility of dispersion destruction depends on how quickly the value of the tangential velocity of the flow in the gap changes along the coordinate r. Unlike other mechanisms of the DPEI, in this case the transformation of energy occurs not in time, but in spatial coordinates [12]. The energy indicator of the efficiency of this mechanism is the “speed” of change of the density of the kinetic energy of the flow in the radial direction of the axis, i.e. the value of $d\varepsilon_k /dr$.

The magnitude of the shear velocity achieved in the RPA gaps depends only on the technical characteristics of the apparatus and is determined by the formula $G = R_{r1}\ \omega/\delta$. For the apparatus sample considered here, $G \approx 600{,}000\ s^{-1}$, which corresponds to the standard values of this parameter in modern industrial apparatus ($10^4...10^5\ s^{-1}$) [2,11]. In accordance with Hooke's law, the magnitude of the tensile stress acting on the particle $P_{sh} = F_\zeta/0{,}5S_m$, where S_m is the area of the midsection of the particle by a plane perpendicular to the flow, and $F_\zeta \propto \zeta P_l S_m^2 G^2$ - is the tensile force. The coefficient of hydrodynamic resistance ζ can be estimated by the formula $\zeta = 2{,}25(16/\mathrm{Re} + 2{,}2\ \mathrm{Re}^{0{,}5} + 0{,}6)$, and the Reynolds number for shear flows is determined by the relation $\mathrm{Re} = \rho_l\ GR^2/\mu_1$. Thus, the magnitude of the tensile stress Psh in shear flows in the gaps of the RPA depends mainly on the Re number, and in accordance with this, the viscosity of the processed liquid mixture should have a decisive effect on the degree of dynamic action. The shear stress acting on a particle in the gaps of the RPA was estimated at $G = 60{,}000\ s^{-1}$ for particles with a diameter d in the range from 1 to 1000 μm at different values of dynamic viscosity in the range from 0,001 to 15 Pa·s. The calculation results are presented in Table 1 for different values of flow viscosity in the specified range of d and μ_c .

Table 1 – Tensile stresses (in MPa) acting in the gap of the RPA on particles of different sizes at different values of the viscosity of the carrier fluid μ_c

d, μm	Viscosity of the liquid phase μ_l, Pa·s							
	0,001	0,01	1,0	2,5	5,0	7,5	10,0	15,0
1	0,0015	0,020	0,049	0,092	0,140	0,182	0,222	0,36
10	0,0065	0,022	0,052	0,103	0,145	0,190	0,226	0,37
100	0,022	0,030	0,105	0,105	0,150	0,205	0,208	0,375
1000	0,08	0,122	0,165	0,203	0,290	0,349	0,400	0,680

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For all given values of flow viscosity μ_c, the magnitude of tensile stresses P in the range 1 μm < d < 100 μm. For larger particles, the magnitude of stresses increases significantly with increasing particle diameter. The values of shear stresses are quite high even for small particles and increase significantly as the viscosity of the carrier phase of the flow increases.

To estimate the size of dispersions destroyed under the action of shear stresses in industrial RPA, information is needed on the nature of the bonds being destroyed and the forces that must be applied to break these bonds in each specific case. The possibility of destroying solid particles in the gap of a rotor-type apparatus solely under the action of shear stresses is shown in [14], where the results of experimental studies of the destruction of small-sized aggregates formed from particles of crushed cement are presented, and data on the magnitude of bonds between particles of aggregates of different sizes are provided. The object of the study was a suspension of crushed cement powder in a water-glycerol solution with a viscosity in the range from 2 to 5 Pa·s. The content of the dispersed phase in the suspension is 2 g/l. The studied mixture was passed through a narrow gap between two cylinders, the outer one of which with a diameter of 108 mm rotated at a high speed. The gap width was 2 mm. The cylinder walls were solid without target holes. The rotation frequency of the outer cylinder in the experiment changed from 50 to 120 s^{-1}, which for the specified gap width corresponds to a change in the shear velocity in the range from 5200 to 13000 s^{-1}.

The tests were carried out with a fraction of particles with diameters in the range of 40…63 μm, of which only 32% were aggregates that could potentially be destroyed using the method under study. Noticeable destruction of aggregates began at a rotor speed of 60 s^{-1}. At a speed of 75 s^{-1}, the effect increased significantly – under this mode, over 10% of particles with a diameter of less than 20 μm appeared in the suspension, which were not present in the original suspension.

The author notes that under the specified material processing conditions, the Reynolds number was within the range of 10...20, so the flow regime was close to the Stokes flow regime.

The results obtained in this work prove the possibility of particle destruction in rotor-type devices only due to shear stresses in the gap without the need for additional consideration of any other mechanisms. In addition, this work indicates the nature of the bonds between particles in aggregates and provides numerical values of the stresses required to destroy cement aggregations by rupturing the particles. Tests have shown that in the experiments conducted under the specified conditions, only aggregates whose particles are bonded by Van der Waals forces can be destroyed. If the particles in the aggregates are sintered or briquetted, the adhesion forces between the particles are two orders of magnitude higher and such formations cannot be destroyed under the experimental conditions. Work [14] presents a table that shows, based on experimental data, what stresses must be created to break the bonds between particles in aggregates of different sizes and destroy these aggregates. We have added columns to this table, which, based on the results of our calculations, show what value of shear stress is achieved under the conditions of the specified experiment when it is necessary to destroy aggregates of a certain size (see Table 2).

Table 2 – Analysis of the destruction of cement aggregates in rotary-type devices according to data from [14]

<table>
<tr><td colspan="2">data of the work [14]</td><td colspan="4">Model calculated results</td></tr>
<tr><td rowspan="3">Initial particl e size, mm</td><td rowspan="3">Bond breaking voltage Van der Waals, kPa</td><td colspan="4">Shear stress, kPa</td></tr>
<tr><td colspan="2">G=5200 c^{-1}</td><td colspan="2">G=13000 c^{-1}</td></tr>
<tr><td>μ_c=2 Pa·s</td><td>μ_c=5 Pa·s</td><td>μ_c=2 Pa·s</td><td>μ_c=5 Pa·s</td></tr>
<tr><td>100</td><td><1</td><td>32,1</td><td>80,1</td><td>82,3</td><td>201,6</td></tr>
<tr><td>10</td><td>1…10</td><td>31,5</td><td>78,2</td><td>78,3</td><td>195,4</td></tr>
<tr><td>1</td><td>100…300</td><td>31,2</td><td>78,0</td><td>78,1</td><td>195,2</td></tr>
</table>

Conclusions

The analysis showed that the RPA of the modification under consideration fully implement the mechanisms of explosive boiling and hydroacoustic cavitation (in the channels of the external stator) and the mechanism of shear stress (in the intercylinder

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gap). The mechanisms of flow acceleration and hydraulic shock (in the channels of the internal stator) are used to a lesser extent. At the same time, it is difficult to make an unambiguous conclusion about which mechanism prevails in each specific case when using industrial RPD to solve specific technological problems [2-10]. Thus, in the work [3] it is shown that the rotary-pulsation apparatus can be successfully used as a disperser at the stage of ultrafine grinding of grain (wheat, barley, corn) in alcohol production. It is noted that the starch contained in the grain endosperm, when processed in the RPA, loses its inherent morphological structure and, as a result of the disruption of internal intercellular connections, acquires the properties of soluble starch, which is the main task of this operation. It is known that the destructive force during compression of the floury endosperm of wheat to release starch grains is 1,7 MPa, and during shear shearing – 0,4...0,6 MPa [5]. For corn grains these indicators are higher. As follows from Table 1, achieving such indicators when using the shear stress mechanism is possible only at extremely high values of the viscosity of the medium (μ_l >10 Pa·s). Apparently, in this case, the cavitation mechanism, which implements strong impact effects and high values of compression and shear stresses at the micro level, makes a significant contribution. In particular, the work [5] provides an example of successful force impact on seeds of various grain crops by abruptly releasing the pressure in the chamber from 0,12…0,17 MPa to 0,1 MPa. This pressure drop causes a sharp change in the grain structure. Plant cells rupture and starch grains swell. It is possible that similar phenomena should arise in the channels of the external stator of the RPA at the stage of rarefaction and explosive boiling of the liquid. When analyzing the operation of RPA used to solve specific technological problems in various industries, it is necessary to take into account and quantitatively evaluate the contribution of each DPEI mechanism to the intensification of this process. This provides the possibility of selecting the most suitable modification of the apparatus and optimal operating parameters in order to successfully solve the tasks set.

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