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Hydrodynamic cavitation – an alternative to ultrasonic food processing

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The paper presents a detailed analysis of the physico-chemical effects of acoustic cavitation used in food processing. The mechanism of interaction between acoustic cavitation and food media is discussed. An overview of recent studies carried out on dairy processing using acoustic cavitation is provided. The acoustic cavitation reactors available in the market are not suitable for large-scale food processing despite positive results obtained with laboratory and pilot scale experiments. Considering a new approach to the theory of cavitation in rotary machines, it has been suggested that hydrodynamic cavitation can be an alternative to acoustic cavitation in food processing applications involving large volumes. A model has been developed that is suitable for the construction of new generation cavitational rotary disintegrators.

Keywords: food sonochemistry, acoustic cavitation, hydrodynamic cavitation, cavitational rotary disintegrator.

INTRODUCTION

Ultrasonic sonochemistry, despite its young age in science, has firmly taken the place of a separate section in high energy chemistry [1]. Now it has separate research areas such as ultrasonic food processing that are actively being developed [2–5]. It promises to solve many problems faced by the food industry, such as the efficient replenishment of moisture lost during the storage and primary processing of edible raw materials. The mankind has been forced to keep the ever-increasing supplies of raw food materials in the dried and frozen form. Therefore, the effective binding of water with food biopolymers – rehydration process – is one of the major problems in the modern food industry. The advantages derived from the addition of water during food processing were established by Henry IV Bolingbroke.

A global scientific community for the first time focused its attention to the importance of water in food in 1974 at the International Symposium «Water relations of food» in Glasgow. Then the Proceedings of the Science Forum, edited by Professor R. B. Duckworth of the University of Strathclyde [6], was released which is now more popular among professionals. Biochemists at the symposium reported that chemically pure protein can theoretically bind up to 40% water by weight as a result of hydration. Hydration shells of protein increase their affinity for water during the precipitation of colloidal systems that can further enhance the hydration of ground biomass.

The hydration process and any reversible chemical reactions move to energetically favorable conditions in accordance with the principle of Le-Chatelier-Brown. As hydration is an exothermic process, it is better when the hydration shell of the protein is built from individual water molecules at the initial stages of the reaction, which can be achieved by pre-ultrasonic treatment. Its action is based on the distribution of water in the periodic pressure pulses that are under the influence of elastic ultrasonic waves emitted by microscopic gas inclusions (cavitation bubbles). Ultrasonic treatment can lead to hydration without heating and does not affect the properties of water, such as its solvation power, structure, etc. Similar mechanisms of action of cavitational restructuring hydration shells of ions in real solution may be responsible for the denaturation of biopolymers in their colloidal solutions and even dispersed phase of sols, and emulsions, that is, in any process in which the object is formed by the impact ion-dipole and dipole-dipole interactions structural connections. Many useful reactions are induced by ultrasound in liquid media: food processing is based on similar such reactions [3, 4]. It is established that the formation of dense and strong hydration shells raise the dissolved thermoresistance valuable nutrients and vitamins, preventing them from thermal denaturation at the subsequent heat treatment [5].

RESULTS OF PRELIMINARY STUDIES

During the ultrasonic processing of food ingredients, routine sonochemical reactions are not desirable. Products generated by reactions in the gas phase inside the cavitation bubbles and subsequently in the liquid phase (induced by primary radicals) should not be present [2, 4] during food processing. In connection with this concept, some studies have identified [4, 7] the safe limits on the usable frequency and intensity of ultrasound. Recommended frequency is 20 kHz and the average amplitude of the reactor sound pressure should be under 2 bar.

For food processing applications, where processing is subject to small amounts of food to several tons a day, ultrasonic equipment is available in various scales. For example, Hielscher Systems GmbH [9] has built ultrasonic equipment for small to large scale processing. One of the Hielscher products, a flow type reactor, meets the engineering prediction of Professor Knapp from University of California, who once wrote that the industrial use of cavitation will be possible only when reactors are built that can handle continuous flow of fluid [10]. A 4 kW flow through ultrasonic was used for the processing of dairy fluids (Figure 1) [11].

It was found that, in spite of the desired frequency ultrasound (20 kHz), with reduced production of free radicals and desired reduction in the viscosity and increased heat stability of protein concentrates, such units have limitations in terms of processing volume (6 L/min). So, where volumes are handled tens of tons or more per day, the use of ultrasonics becomes a problem. For processes with small production quantities, such as moistening the grain before grinding or «wet» salted minced meat [12, 13] in studies conducted in Moscow [4] the ultrasonic cavitation reactor, РКУ-0,63 was used. It was intended for the production of brine for minced meat processing, where about 1-2 tons of brine solution could be treated corresponding to 50-80 tons of processed meat per shift.

Figure 1. Pilot-scale experimental setup used in dairy processing using *Hielscher Systems GmbH* UIP-4000 (Figure adapted from [11])

In this regard, it has to be recognised that hydrodynamic cavitation was introduced more than half a century ago in the processes of homogenization, dispersion and emulsification [2, 14]. Cavitation is generated due to constrained fluid flow. Technology in this field has made a great progress in recent years. One of the first explorers of the hydrodynamic cavitation, Dr. J. Hint in Estonia, continued to engage in traditional rotary hydrodynamic disintegrantors. Hint was the first who noticed in the process of mechanical disintegration that not only dispersion, but some other important physico-chemical properties of processed materials are changed: this has introduced the concept of «*disintegrational activation*». Later he began to write about the activation of liquid media in mechanical disintegrators [15]. The phenomenon of activation of the rotary-pulse devices will soon become uniquely associated with the action of cavitation [16]. But only in this century, the disintegration of fluids as a result of erosive effects of hydro [17] or acoustic cavitation has been highlighted and an independent term «*cavitational disintegration*» [18] has been established.

Studies on the generation of oil-water emulsions using cavitational disintegrators on board of a *Pacific Ocean Shipping Company Ltd* ferry showed a high water content in the emulsions. The effect can be attributed solely to the hydration reaction. Bunker oil is a substance with polar molecules such as naphthenic acids and resin-asphaltene compounds. These are different from petroleum hydrocarbons of higher molecular weight and the presence of oxygen, sulfur and nitrogen hetero-atoms [19] provides them with the polar groups. In the process of emulsification in the rotary-pulsed apparatus, they react with the water that is subjected to cavitation disintegration. The hydration process increases the hydrophilicity of these substances and contributes to the formation of structural and mechanical layers at the interface of emulsion, increasing its dispersion and improves the conditions of combustion.

These hydration reactions are also important in food processing applications of acoustic cavitation. After all, the components of the protein molecules in the hydration reaction of amino acids involved active polar centers represented the carboxyl -COOH, hydroxyl -OH and amino $-NH_2$ groups. The binding of water to protein molecules results in hydration structures (Figure 2).

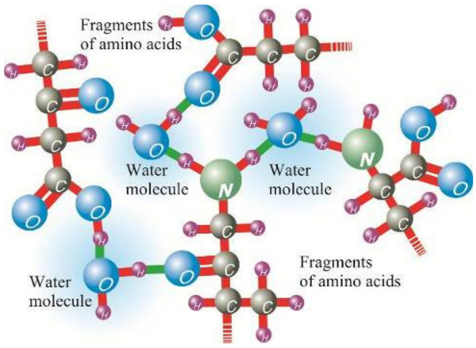
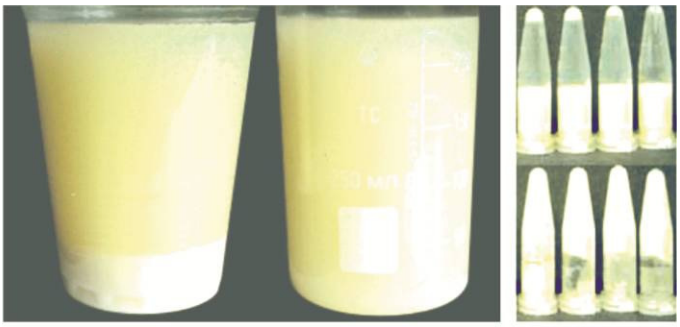


Figure 2.

Hydration and structuring of proteins

Studies have shown that ultrasonically treated water results in better hydration of proteins, stabilized against separation and precipitation, resulting in complete dissolution of proteins (Fig. 3a). However, the structuring of protein leads to an increase in the viscosity of protein solutions and changing the syneresis process, which is not always a positive feature. Some investigations on the effects of ultrasound on whey proteins were aimed at expanding the parameters used in subsequent stages of heat treatment technology and to facilitate the process of ultrafiltration. This involves the need to reduce the viscosity and prevent the formation of protein aggregates [3, 20].

The desired effects cannot always be achieved by a separate water treatment, as previously recommended. The ultrasonic treatment of aqueous solutions of whey protein, WPC 80 (Figure 3b) resulted in an increase in viscosity under specific experimental conditions. It can be clearly seen that the sonication effect in terms of increasing the solubility of proteins differ from the effect of heat stability.



a). b).

Figure 3. a) Reconstituted whey, left without sonication, right with the sonication at 22 kHz, 90 W/L, 1 min. b) solution of whey protein from WPC 80 in the top row without treatment, the bottom with treatment at 20 kHz, 31 W, 60 min. Post heating to +80°C for 10, 12, 14 and 16 minutes (left to right)

THEORY

Due to the shortcomings of ultrasonics processing, a new look at the hydrodynamic method has emerged for producing cavitation and for the possibility of its use in food processing. Here, we describe hydrodynamic cavitation disintegrators, which are based on the hypothesis of Hint. It can be expressed by the following quote from his essay: «*... the more the number of strokes imparted by particulate matter, the greater the impact velocity and the smaller the interval between successive blows, the more there is activity*». From this assessment, similar representations of disintegrators are set forth in the development of rotary-pulse devices, where the efficiency of hydrodynamic cavitation is increased by increasing the rate of fluid flow and interruptions to the flow rate. The main factor is the kinetic energy of the fluid flow, which is proportional to the square its velocity [15, 16]. It is easy to realize in such rotor-switching device that processing 10 t/h of fluid, at a speed of 300 s^{-1} using a rotor diameter of 150 mm which can be achieved using a 10×20 mm channel. The flow of the processing liquid occurs as long as these channels have openings with little more than a tenth of a millimeter. When gas bubbles move from a high to a low pressure zone, they do not survive [10]. The sudden drop in pressure leads to the growth and the eventual collapse of these gas bubbles, referred to as hydrodynamic cavitation. In rotary disintegrators, the effects are not just due to the liquid flow alone – additional forces are generated due to hydrodynamic cavitation. Here, we should use a slightly different approach to assessing efficiency than commonly used. The pulsations of cavitation bubbles and the shock waves that emanate from them can be major forces causing cavitation erosion [21, 22], which in the theory of vibrations and waves can be estimated by finding the value of the deformation of rarefaction and compression, that is, determining the magnitude of the potential component of the scattered energy in a fluid [10]. Cavitation power is proportional to the square of the acoustic pressure. It depends not so much on the changes in pressure caused by the discontinuity of fluid flow through channels in the radial direction, but it is generated by movement relative to the profile of transversal section of the rotating rotor, which is due to the presence of periodically repeating holes.

The latter can be confirmed by looking at the homogenizers manufactured by *Aquametro AG*, in which the fluid does not flow in the radial direction but axially in the gap between deaf equipped with grooves facing each other on the walls of the rotor while the stator cross-sectional area remains constant (Figure 4a). Among the rotary disintegrators widely used, for example, where the rotor and stator are used with one or more cylindrical shells of finite length at the bottom, fluids flow through the hole of rectangular shape. The rotor and stator create a working volume between the top and the bottom of one another, fluid flows through the axis to the periphery of the construction in the radial directions by opening and closing of the rotating liquid flow channels (Figure 4b). Mathematical model of cavitation in a disintegrator may be based on differential equations of Hickling-Plesset or Rayleigh-Plesset [21, 23] for vapor cavity wall motion under the influence of strain and stress, as described in some problems of solid mechanics theory of functions of complex variables. The mechanical stress in the fluid, that is, the pressure at any point, can be estimated on the basis of conformal mapping. In order to apply stress to a flat region, z profile of the liquid in a rotary disintegrator, which has a uniform distribution of stress, strains such as an infinite strip of constant width (Figure 4c,d), the Schwarz-Christoffel integrals, can be used.

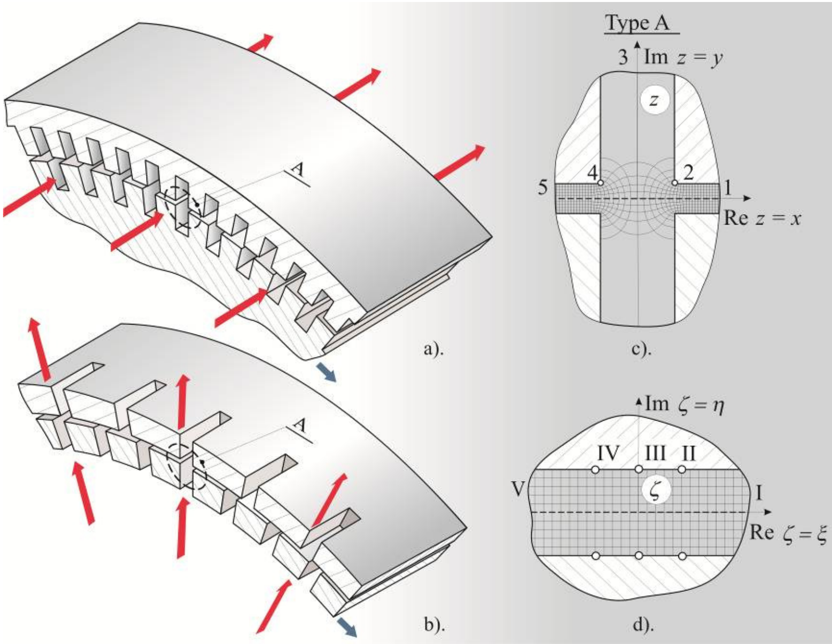


Figure 4. Schematic design of rotor and stator homogenizer (Swiss company *Aquametro AG*). The device with the rotor and stator in the form of cylindrical shells, which are made by rectangular holes. Red arrows indicate the direction of fluid motion, blue – the rotation of the rotor. On the right the cross section is shown – the lines show stress-strain fluid having a rheological equation of state of the limit nature, as in an absolute elastic body, and the current without friction, obtained by conformal mapping shown at the bottom of the invariant for this section. Arabic and Roman numerals indicate the corresponding angles

Such a model should consider the liquid friction on the structural elements of the cage, and thus the rheological equation of state has a limit, i.e., it is completely flexible. In calculating the absolute values of the characteristics of these conditions are not quite correct, but in the comparison of similar operations on the same liquid, they are quite acceptable, especially if the cavitation bubble on the wall behaves as a Newtonian fluid according to Hickling-Plesset equation. Mechanical stress at any point can be expressed in terms of the pressure in the working volume, p_0, derivative of the mapping function to map this point onto the invariant ζ:

$$\sigma = \frac{p_0}{\dot{z}^2}, \text{ where } \dot{z} = \frac{\mathrm{d}z}{\mathrm{d}\zeta}. \qquad (1)$$

It is clear that the exponent at $\dot{z}$ is 2 only if all the profiles of fluid flow plane-parallel to each other. The nature of the elastic strain and stress, as well as their behavior in a batch of microscopic inclusions of steam in the liquid can be determined by numerical simulations. They allow for numerical comparisons. The behavior of the cavitation bubble was performed by numerical integration of Hickling-Plesset equation by Runge-Kutt method. The periodic variation of pressure in the liquid was substituted appropriately (1) with a derivative of the function display strip to the diametrical cross section of one of the holes in the rotor, one of the holes in the stator and the gap between them:

$$z = \frac{\delta}{\pi}\operatorname{Arth}\frac{\operatorname{sh}\frac{\pi}{2}\zeta}{\sqrt{\operatorname{ch}^2\frac{\pi}{2}\zeta + \frac{a^2}{\delta^2}}} + \frac{a}{\pi}\operatorname{arctg}\frac{a\operatorname{sh}\frac{\pi}{2}\zeta}{\sqrt{\delta^2\operatorname{ch}^2\frac{\pi}{2}\zeta + a^2}}, \tag{2}$$

where: a – width of the opening (the size of the diameter); δ – the gap between the stator and rotor; ζ – coordinate on the invariant expressed by the complex number $\xi + j\eta$. Its derivative is equal to ζ:

$$\dot{z} = \sqrt{1 + \frac{a^2}{\delta^2(2 + e^{\pi\zeta} + e^{-\pi\zeta})}}. \tag{3}$$

Reciprocal of the square of $\dot{z}$ is proportional to the tensile deformation of the fluid at any point of the section, causing a pressure change:

$$p \sim \frac{\delta^2(2 + e^{\pi\zeta} + e^{-\pi\zeta})}{\delta^2(2 + e^{\pi\zeta} + e^{-\pi\zeta}) + a^2}. \tag{4}$$

To calculate the change in pressure points on the real axis for a total period of the invariant, the coordinate must vary in the range $\pm\xi$. The time during which a corresponding change in pressure occurs will be $T = \frac{\xi}{\omega\pi R}$, where R is the outer radius of the rotor, and is the minimum allowable period of pressure on the elastic deformation of the liquid ξ is a root of the transcendental equation:

$$\varepsilon = 1 - \frac{\delta^2(2 + e^{\pi\xi} + e^{-\pi\xi})}{\delta^2(2 + e^{\pi\xi} + e^{-\pi\xi}) + a^2}, \tag{5}$$

where $\varepsilon = 0{,}05$ – margin of error in relative units.

The quantification of the effectiveness of cavitation can be estimated from the increment of the extent of erosion [22]. A comparative assessment of its value can be estimated using conditional parameters, ΔP – erosion of unit capacity, that is, the extra power released in the pressures on the wall during the collapse, $p_{max} > p_0$, the maximum for the pulse of its volume V_{max} conventionally located in each channel in the middle of the stator and rotor clearance a cavitation:

$$\Delta P = \frac{\beta}{2}\omega V_{max} N n (p_{max} - p_0)^2, \tag{6}$$

where: β – adiabatic compressibility of the fluid; ω – rotor speed; N – number of channels in the rotor, n – in the stator. The model was implemented in a computer program. Water was chosen as the liquid.

EXPERIMENTS

A computer experimental analysis was made on the behavior of bubbles with a diameter of 10 µm using the model in accordance with (1) – (6) and on the basis of information contained in [17]. It was also verified by the measurement of the power of sound near the stator of the experimental cavitational disintegrator (Figure 5), at the frequency at which the cavitation noise was expected, using equation (7):

$$f = 2\pi R \frac{\omega}{\delta z}, \text{ at } \zeta = \xi \qquad (7)$$

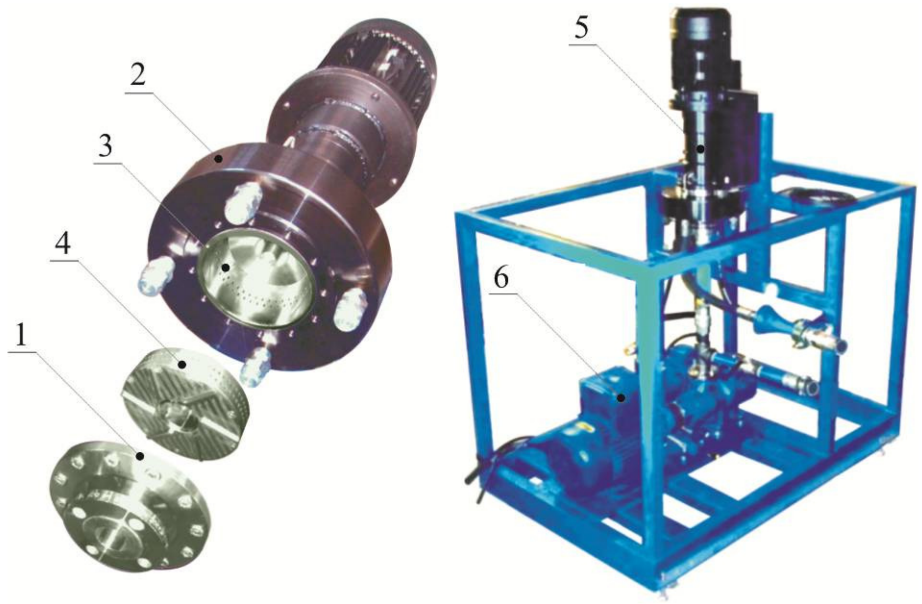


Figure 5. Photos of the prototype rotary cavitation disintegrator with a cover sealing the lid of the working volume 1 and withdrawn from stator 2 the rotor 3 and left: apparatus, consisting of a rotary disintegrator 4 and feeder screw pump 5

An oil-in-water emulsion containing 20% aqueous phase was treated in the disintegrator. The power level of cavitation in the aqueous phase was determined using (8):

$$P_{\text{cav}} = 10 \cdot \lg(10^{0,1P_{\text{em}}} - 10^{0,1P_{\text{oil}}}), \qquad (8)$$

where: P_{em} and P_{oil} are the measured noise levels in dB near the surface of the working chamber 2, at the frequency of opening channels during the rotation of the rotor relative to stator (8,7 kHz), during the processing of emulsions and oils, respectively.

The overall noise levels observed in the experiment using the prototype cavitation disintegrator was 100 dB when it was operated at its peak power. However, the apparatus shown in Figure 5 was not sound proof. In the industrial version of the device a special sound proofing cage will be included to reduce its noise level.

The results of calculations and experiments for actual specifications and dimensions of structural elements disintegrator, $\omega = 44,17$ s^{-1}, $\delta = 30$ µm, $R = 0,142$ m are shown in Figure 6.

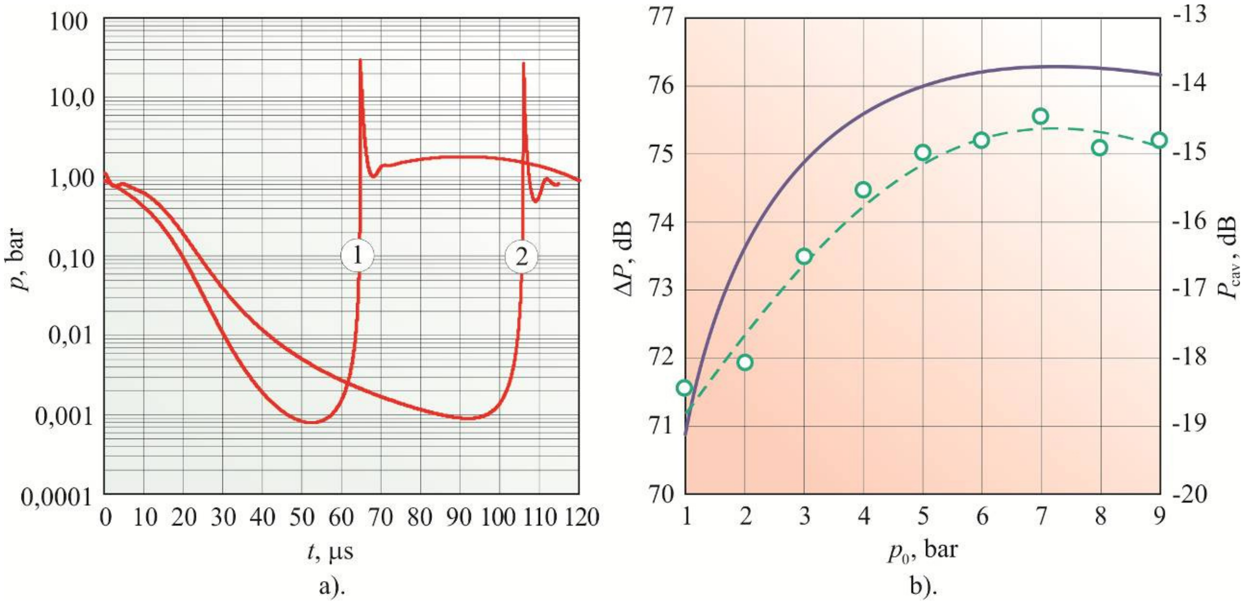


Figure 6. a) Pressure on the surface of a cavitation bubble as a function of time: 1 – at the antinode of acoustic waves of frequency 20 kHz with an amplitude of sound pressure 1,2 bar; 2 – in the gap between the stator and rotor of the disintegrator, b) calculated ΔP (blue), measured with low gain P_{cav} (green), depending on the p_0 , - - - polynomial degrees 3

CONCLUSIONS

The research outcome using laboratory-scale equipment for a scientific problem may not always be useful in large-scale processing. Such problems can be overcome by appropriate alternatives that are suitable for large scale processing. Experimental and theoretical studies have shown that cavitation rotary disintegrators may be suitable for large-scale processing in food industry, where hydrodynamic cavitation is found to be an alternative to acoustic cavitation for processing large volumes of liquid media. The concept of the hydrodynamic disintegrator fully meets the established requirements of the frequency and intensity of ultrasound in food processing.

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